Research Article

An acoustic study of contextual tonal variation in Tianjin Mandarin

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ABSTRACT

The $f0$ realization of lexical tones is known to vary greatly due to contextual tonal variation processes such as tone sandhi and tonal coarticulation. This study set out to investigate the $f0$ variability induced by these two different sources with well-controlled acoustic data from Tianjin Mandarin. Tianjin Mandarin is known for its complex patterns of tonal variation over disyllabic constituents, as well as for the conflicting directionality of sandhi alternations and possible iterative application of disyllabic sandhi rules over trisyllabic constituents. Previous studies on Tianjin tone sandhi have often been based on impressionistic descriptions of speech produced by speakers of older generations. In this study, we investigated the $f0$ realization of disyllabic and trisyllabic tonal sequences in Tianjin Mandarin produced by younger speakers (born in the 1980s). Through examining $f0$ variation of lexical tones as a function of different following tones, we observed an interesting anticipatory raising effect of the lexical low-falling tone (T1). Furthermore, we confirmed three tonal sequences with tone sandhi changes: (1) two low-falling tones (T1T1), (2) a high-falling tone followed by a low-falling tone (T4T1), and (3) two low-dipping tones (T3T3). These disyllabic tone sandhi patterns, however, were not consistently observed within trisyllabic sequences, as claimed in the literature. Specifically, while T3T3 showed sandhi application regardless of its position within a trisyllabic sequence, T1T1 and T4T1 sequences showed sandhi changes only when they were right aligned. Last but not least, no tonal neutralization was observed over any of the sandhi processes. Rather, we argue that T3T3 is a near-merger sandhi case, while T1T1 and T4T1 can be classified as no-merger sandhi sequences.

1. Introduction

It is known that the $f0$ realization of lexical tones varies extensively in connected speech. At a global level, $f0$ can vary due to the overall discourse prosody in which the tone-bearing lexical item is produced. At a more local level, the $f0$ realization of a lexical tone can be further affected by its neighboring tones (see e.g., Chen, 2012 for a review). One well-noted local contextual effect is tone sandhi, which is often described as the phonological change of lexical tones (Chen, 2000; also see Zhang, 2010 for a review). Another local contextual effect is tonal coarticulation, which is traditionally defined as phonetically minor $f0$ adjustments to preceding or following tones (see Xu, 2001 for a review). Both processes cause changes in the $f0$ realization of a lexical tone, so that the resulting $f0$ contour may deviate to varying degrees from the canonical $f0$ shape of the tone produced in isolation. While there has been general agreement on the difference between tonal coarticulation and tone sandhi to account for contextual tonal variation, there is little consensus or research effort on how exactly or whether the wide range of $f0$ deviations can be categorized as a function of these two distinct processes.

In this study, we aimed to address this issue through directly comparing these two types of tonal variation. Our empirical base is Tianjin Mandarin, a Northern Mandarin dialect spoken in the urban areas of Tianjin, a metropolis in northern China. Tianjin Mandarin presents an interesting test case on tonal variation, further understanding of which will shed light on how different tonal variation processes intertwine to determine the $f0$ realization of lexical tones. The dialect is known for its complex tone sandhi patterns over disyllabic constituents. Over trisyllabic constituents, some tone sandhi rules have been argued to apply only to the leftmost two syllables, while others only to the rightmost two syllables, regardless of the morpho-syntactic structures. Furthermore, some sandhi

rules are claimed to apply iteratively, i.e., over derived contexts of the first round of sandhi application. These two properties are together known as the "paradox" in Tianjin tone sandhi (e.g., Chen, 2000).

It is important to note that although tonal variation in Tianjin Mandarin has been extensively studied, most were based on impressionistic data. In a recent acoustic study, Zhang and Liu (2011) examined tonal coarticulation of disyllabic items but did not compare them to the previously claimed tone sandhi patterns. This makes it impossible to evaluate directly how tonal variation due to different sources may differ. Furthermore, despite the potentially significant implications of the Tianjin Mandarin tone sandhi "paradox" on our theoretical modeling of tonal variation, no experimental work has been done on trisyllabic tone sandhi in Tianjin Mandarin. Pilot results in Li and Chen (2012) raised serious doubts on the tonal variation patterns of trisyllabic sequences reported in the literature (Chen, 2000 and references therein).

The specific goal of this study therefore was to collect data from a well-controlled acoustic experiment and investigate (1) how lexical tones are realized with varying $f0$ contours in disyllabic domains without pre-exclusion of any tonal sequence claimed to involve tone sandhi processes; and (2) whether disyllabic tone sandhi alternations can be observed in trisyllabic constituents, with particular focus upon the issue of directionality and iterativity of sandhi application. By doing so, we hope to arrive at a better understanding of tonal realization in Tianjin Mandarin, which, in turn, would help to further refine a general theory of tonal variation.

1.1. Lexical tones of Tianjin Mandarin in isolation

Although Tianjin Mandarin has a very similar segmental structure to Standard Chinese, the dialect differs significantly from Standard Chinese in terms of the tonal system (Han, 1993; Wee, Yan, & Chen, 2005). There are four lexical tones in Tianjin Mandarin. Fig. 1 illustrates the $f0$ realization of the four lexical tones elicited in isolation. All $f0$ contours were plotted based on 50 samples with different segmental structures for each tone, produced by a male native speaker in his 20s at the time of recording (born in 1983). $f0$ contours were time-normalized by taking 20 points in the rhyme part of each syllable with equal time interval. The $f0$ values were normalized by converting them to speaker-specific z-scores (Rose, 1987) with the formula: $z=\frac{f0_x - f0_{mean}}{f0_{SD}}$. ($f0_x$: the observed $f0$ value in Hz; $f0_{mean}$: the mean $f0$ value of the speaker in Hz; $f0_{SD}$: the standard deviation of $f0$ value of the speaker in Hz.)

As can be seen from Fig. 1, Tone 1 is a low-register falling tone, with a pitch contour that falls from the middle to the lower end of the speaker's pitch range. Tone 2 is a high-register rising tone, whose pitch contour rises from the middle to the upper end of the pitch range. Tone 3 is a low-register dipping tone, which falls slightly from the lower pitch range, stays at the bottom and then rises to the mid pitch range of the speaker. Tone 4 is a high-register falling tone which falls from the upper end to the mid pitch range.

Table 1 summarizes the annotations adopted in different studies. Strictly speaking, no annotation system listed in Table 1 accurately reflects the $f0$ contours plotted in Fig. 1. This discrepancy is in part an indication of the considerable variation in lexical tone production that exists both within and across speakers of the same generation as well as across speakers of different generations. Despite the variability, the basic $f0$ patterns of the four lexical tones are rather consistent at a more abstract level.
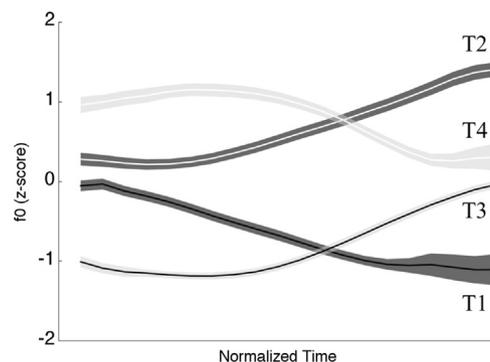
Fig. 1. Four lexical tones in Tianjin Mandarin produced in isolation (with normalized time). Lines stand for the mean. Gray areas stand for ± 1 standard error of the mean.

Table 1
Transcriptions of the four lexical tones in Tianjin Mandarin in different studies.

T1	T2	T3	T4	
L	H	R(LH)	F(HL)	For e.g., Chen (2000), Wee et al. (2005), Hyman (2007)
LL	HH	LH	HL	For e.g., Wang and Jiang (1997); Wang (2002); Ma (2005)
21	45	213	53	For e.g., Li and Liu (1985), Hung (1987), Tan (1987), Zhang (1987) and Han (1993)
211	455	113	553	For e.g., Shi (1986)
41	34	12	52	For e.g., Zhang and Liu (2011)

1.2. Tonal variation in connected speech in Tianjin Mandarin

In connected speech, tonal variation abounds in Tianjin Mandarin. Of our interest are the two processes that have been described in the literature to extensively influence the *f*0 contour of a lexical tone within a local tonal context: tonal coarticulation and tone sandhi.

1.2.1. Tonal coarticulation

Tonal coarticulation has been reported in many East Asian contour-tone languages, such as Thai (e.g., Palmer, 1969; Abramson, 1979; Gandour et al., 1993; Gandour, Potisuk & Dechongkit, 1994; Gandour et al., 1996; Potisuk, Gandour & Harper, 1997; Zsiga & Nitisaroj, 2007), Vietnamese (e.g., Han & Kim, 1974; Brunelle, 2009), Standard Chinese (e.g., Shen, 1990; Xu, 1994; Xu, 1997; Kochanski, Shih & Jing, 2003), Taiwanese (e.g., Peng, 1997; Wang, 2002), and Malaysian Hokkien (e.g., Chang & Hsieh, 2012). Despite the differences among languages, two types of tonal coarticulation have been commonly attested: the left-to-right carryover tonal coarticulation and the right-to-left anticipatory tonal coarticulation.

Carryover tonal coarticulation refers to the effect that the production of the first tone has on its following tone in a disyllabic tonal sequence. Carryover effects are generally assimilatory in nature (e.g., Han & Kim, 1974; Abramson, 1979; Shen, 1990; Gandour et al., 1994; Potisuk et al., 1997; Xu, 1997; Brunelle, 2009). Therefore, the high *f*0 offset of the first tone raises the *f*0 onset of the second tone, while the low *f*0 offset lowers the following onset. Such tonal coarticulation patterns have been observed consistently across languages regardless of the identity of the first tone. Due to the carryover effects, the onset of the second tone usually varies greatly. The influence from the preceding tone can be extended well into the first half or the entire second tone, although the magnitude of the influence decreases over time (e.g., Gandour et al., 1993, 1994; Potisuk et al., 1997; Xu, 1997; Brunelle, 2009).

The cross-linguistic carryover effects have been reported for Tianjin Mandarin in Zhang and Liu (2011). Specifically, they argued that three tones in Tianjin Mandarin are subject to the carryover effects, i.e., T2, T3, and T4. The low-falling tone (T1), however, was claimed to resist the carryover effects from any preceding tone.

In contrast to carryover effects, anticipatory tonal coarticulation refers to the effect of a following lexical tone on the production of its preceding tone. Anticipatory effects are mainly dissimilatory in nature (but see Shih and Konchanski, 2000 for reported assimilatory anticipatory effects in Standard Chinese), and are usually restricted to a limited number of triggering contexts. The magnitude and the temporal extent of their influence are also much less (e.g., Gandour et al., 1994; Potisuk et al., 1997; Xu, 1997; but see Chang & Hsieh, 2012 for more powerful anticipatory effects reported for Malaysian Hokkien). In a disyllabic tonal sequence, the anticipatory effects seem to be triggered only by a following low tone (e.g., Gandour et al., 1994 and Xu, 1997 for Thai and Mandarin, respectively). In most cases, anticipatory effects on the first tone are also rather negligible and localized to the offset of the preceding tone (e.g., Potisuk et al., 1997; Xu, 1997).

In Tianjin Mandarin, only a minor anticipatory effect has been reported, which is triggered by the low-register dipping T3 (Zhang & Liu, 2011). It is important to point out that Zhang and Liu (2011) did not examine tonal combinations that were assumed to involve tone sandhi for potential anticipatory effects. This makes our understanding of the anticipatory tonal coarticulation effects in Tianjin Mandarin possibly limited and incomplete. Given that in Tianjin Mandarin, tone sandhi is right dominant and anticipatory coarticulation is also triggered by the second syllable within a disyllabic word, we think it is particularly important that we include all possible tonal combinations to shed further light on the potential differences between tonal coarticulation and tone sandhi.

1.2.2. Tone sandhi

Different from tonal coarticulation that is usually considered the phonetic modification of *f*0 contours, tone sandhi, in many of the impressionistic reports, is considered to involve the categorical change of the phonological identity of a lexical tone. Much work has been done on tone sandhi in various Chinese dialects (see e.g., Chen, 2000 for an overview), among which Tianjin Mandarin is known for its complex sandhi patterns over disyllabic and trisyllabic constituents.

For disyllabic sequences, most previous studies on Tianjin Mandarin have identified four disyllabic tone sandhi rules (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Ma & Jia, 2006; Hyman, 2007), as shown in Rules (1)–(4), where the tones were transcribed with features adopted from Chen (2000).

(1) T1+T1 (L+L)→T3+T1 (LH+L)
(2) T3+T3 (LH+LH)→T2+T3 (H+LH)
(3) T4+T4 (HL+HL)→T1+T4 (L+HL)
(4) T4+T1 (HL+L)→T2+T1 (H+L)

Rules (1)–(3) have been attributed to tonal dissimilation due to the Obligatory Contour Principle, while Rule (4) is attributed to Tonal Absorption (Chen, 2000). With sociolinguistic data, Lu (1997) proposes that Rule (1) has undergone some diachronic changes. A new pattern of that sandhi change, i.e., T1+T1 (L+L)→T2+T1 (H+L), has been observed in the speech of the younger generation. In addition, Rule (4) has been reported to become "obsolete" in the speech of the younger generation (Liu & Gao, 2003). More recently, Wee et al. (2005) argued that there are two more sandhi rules in Tianjin Mandarin, where T3 changes to T1 before either T2 or T4 as shown in Rules (5) and (6).

(5) T3+T2 (LH+H)→T1+T2 (L+H)
(6) T3+T4 (LH+HL)→T1+T4 (L+HL)

What is shared among all the impressionistic studies is that tone sandhi involves the categorical change of one lexical tone to another within the native lexical tonal system. However, recent experimental data suggest that in Tianjin Mandarin, tonal neutralization might not be involved at all in disyllabic tone sandhi (Zhang & Liu, 2011; Li & Chen, 2012).

For trisyllabic sequences, the tone sandhi situation becomes more complicated. Of all 64 tonal combinations of trisyllabic sequences, 27 have been claimed to involve sandhi based on the four commonly accepted disyllabic sandhi rules (e.g., Li & Liu, 1985; Chen, 2000; Ma, 2005; but see Wee et al., 2005 for more trisyllabic sequences that undergo sandhi changes).

Among the 27 combinations, 20 have been referred to as simple applications, where only one disyllabic sandhi rule could possibly apply. These disyllabic patterns have been argued to apply consistently within a trisyllabic domain, regardless of the location where the disyllabic combinations occur. For example, T1T1 sandhi is claimed to apply over both T1T1T2 and T2T1T1.

The other seven cases (7)–(13) have been claimed to involve iterativity and directionality issues of sandhi applications (e.g., Li & Liu, 1985; Chen, 2000; Ma, 2005). Specifically, (7)–(11) have been claimed to involve iterative sandhi rule application, due to a newly-derived sandhi context after the first round of sandhi application. For example, in the sequence T3T1T1 (10), the first T1 is claimed to change to T3, which results in an intermediate stage T3T3T1 where T3T3 is again a possible sandhi context, leading to the final output as T2T3T1.

	Underlying pattern		1st round of application		2nd round of application
(7)	T3+T3+T3 (LH+LH+LH)	→	T2+T3+T3 (H+LH+LH)	→	T2+T2+T3 (H+H+LH)
(8)	T4+T4+T1 (HL+HL+L)	→	T1+T4+T1 (L+HL+L)	→	T1+T2+T1 (L+H+L)
(9)	T4+T4+T4 (HL+HL+HL)	→	T4+T1+T4 (HL+L+HL)	→	T2+T1+T4 (H+L+HL)
(10)	T3+T1+T1 (LH+L+L)	→	T3+T3+T1 (LH+LH+L)	→	T2+T3+T1 (H+LH+L)
(11)	T1+T4+T4 (L+HL+HL)	→	T1+T1+T4 (L+L+HL)	→	T3+T1+T4 (LH+L+HL)
(12)	T1+T1+T1 (L+L+L)	→	T1+T3+T1 (L+LH+L)		
(13)	T4+T1+T1 (HL+L+L)	→	T4+T3+T1 (HL+LH+L)		

The seven cases here have also been argued to exemplify the directionality of tone sandhi changes. (7) and (8) have been argued to undergo sandhi processes from the left edge and (9)–(13) from the right edge. Taking the tonal sequence T1T1T1 (12) as an example. This sequence has been reported to surface as T1T3T1, which has been taken as evidence that the sandhi rule must have been applied from the right edge of the constituent instead of the left edge.

Various attempts have been made to explain the complex sandhi application in Tianjin Mandarin (e.g., Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; Ma, 2005; Wee et al., 2005), but no consensus has been reached. The issues of iterative and directional applications of tone sandhi in Tianjin Mandarin not only have presented great challenges to phonological theories of tonal alternation, but also have raised interesting questions regarding theories of allotone processing and learnability.

Before any attempt to address these theoretical issues is made, two problems need to be tackled with regard to the proposed trisyllabic sandhi rules. First, since the disyllabic combinations have been shown to be realized differently from what has been claimed in the literature, it is very likely that the actual realization of trisyllabic combinations might also differ from those described in previous studies. Second, the so-called iterative sandhi application proposed for some trisyllabic combinations is based on the assumption that sandhi-derived tones are lexical tones within the system and there is complete neutralization of the derived and the base tones. If indeed tone sandhi in Tianjin Mandarin does not involve lexical tone neutralization, any iterative tonal change is then called into question. At this stage, we believe that well-controlled experimental data are not only needed but also crucial for our further understanding of these issues.

2. Method

Disyllabic tonal sequences with full combination of the four lexical tones ($T_{1-4}T_{1-4}$) were collected to allow direct comparison of the two possible types of tonal variation, i.e., tonal coarticulation and tone sandhi in the language. To investigate further the iterativity and directionality of tone sandhi application, relevant trisyllabic sequences were also included. Subsets of the data will also provide us with evidence to shed light on the issue of tonal neutralization under sandhi changes.

2.1. Materials

We used real words and phrases because most of our speakers reported to have difficulties in producing nonsense sequences (see also Zhang & Liu, 2010 for different tonal realization of nonsense words compared to real words). Two reading lists were included in this study, one for the disyllabic sequences and the other for the trisyllabic sequences.

The disyllabic reading list consisted of all 16 possible tonal combinations of the four lexical tones in Tianjin Mandarin. All stimuli are common collocations, which are arguably lexicalized in the language. For possible influence from their internal morpho-syntactic structures, we limited the structures to three different combinations: Compound (e.g., 爹妈 die[1]ma[1] "*parent*"), Modifier+Head (e.g., 鸵鸟 tuo[2]niao[3] "*ostrich*"), and Verb+Object (e.g., 推理 tui[1]li[3] "*inference*"). These morpho-syntactic structures had a balanced number for each tonal combination. The choice of the stimuli was further constrained by their segmental composition. Only sonorant onsets were used for the second syllables in order to better observe the effect of contextual tonal variation and also for the ease of segmentation.

The trisyllabic reading list included all 64 combinations of the four lexical tones. For each trisyllabic tonal combination, the sequence was either a mono-morphemic word (σσσ, as mostly seen in loan words such as乌拉圭 <u>wu</u>[1]<u>la</u>[1]<u>gui</u>[1] "*Uraguay*"; hereafter, underlines indicate the constituent structure of the sequence), or a compound or phrase with two different internal grouping patterns: σσ+σ (e.g., 拉丁舞 <u>la</u>[1]<u>ding</u>[1] <u>wu</u>[3] "*Latin dance*") or σ+σσ (e.g., 高工资 <u>gao</u>[1] <u>gong</u>[1]<u>zi</u>[1] "*high salary*"). For each structure, we included two different items. Due to the limited availability of syllables with sonorant onsets, items with obstruent onsets at the second and third syllable were also used. Most test items are very common words and phrases with an exception of a few, which nevertheless are still relatively common.

Each test item was embedded in a unique carrier sentence with the copular verb "… shi[4] … ('… *is* …')." The length of each carrier sentence was within the range of 9–11 syllables as illustrated in the following example, where the target stimulus is密码 (mi[4] ma[3], "*password*").

密码	是	种	保密的	手段。
<u>Mi</u>[4] <u>ma</u>[3]	shi[4]	zhong[3]	bao[3] mi[4] de	shou[3] duan[4].
Password	BE	Classifier	encrypting	method.
Password is an encrypting method.				

Data from Chen and Gussenhoven (2008) and Chen (2010) for Standard Chinese as well as Scholz (2012) and Scholz and Chen (2014) for Wenzhou Chinese show that lexical tones are less influenced by adjacent tonal targets when produced under focus, compared to their post-focus counterparts. (Readers are also referred to Chen, 2012 for further discussions on the effects of on-focus vs. post-focus on tonal realization.) To control the effect of focus, we elicited the utterances as answers to specific questions, resulting in two focus conditions, as illustrated below. In the On-Focus condition, focus was on the target phrase. In the Pre-Focus condition, focus was on later parts of the sentence. In this way, we excluded the possibility that speakers might randomly produce the stimulus sentences with varying information structures. For this particular study, we were not interested in the effect of focus per se and had therefore placed the target stimuli in the sentence-initial subject position, where we knew that the effects of on-focus and pre-focus are closer than in other positions (Xu, 1999).

On-Focus condition:

QUESTION:	什么	是	种	保密的	手段？
	Shen[2] **me**	shi[4]	zhong[3]	bao[3] mi[4] de	shou[3] duan[4]?
	What	BE	Classifier	encrypting	method?
	***What** is an encrypting method?*				

ANSWER:	密码	是	种	保密的	手段。
	Mi[4] **ma**[3]	shi[4]	zhong[3]	bao[3] mi[4] de	shou[3] duan[4].
	Password	BE	Classifier	encrypting	method.
	***Password** is an encrypting method.*				

Pre-Focus condition:

QUESTION:	密码	是	种	什么？	
	Mi[4] ma[3]	shi[4]	zhong[3]	**shen**[2] **me**?	
	Password	BE	Classifier	**what**?	
	***What** is password?*				

ANSWER	密码	是	种	保密的	手段。
	Mi[4] ma[3]	shi[4]	zhong[3]	**bao**[3] **mi**[4] **de**	**shou**[3] **duan**[4].
	Password	BE	Classifier	**encrypting**	**method**.
	*Password is an **encrypting method**.*				

2.2. Subjects

Six speakers (3 males and 3 females) participated in the experiment. All were local college students, born in the 1980s and raised in the urban areas of Tianjin. None of them had lived outside of Tianjin. They were paid for the participation but unaware of the purpose of the experiment.

2.3. Recording

All questions were recorded beforehand in the Phonetics Lab at Leiden University by a native speaker of Tianjin Mandarin. During the experiment, subjects were requested to respond to the question with the targeted response sentence presented on the computer screen. All found the task straightforward and followed the same procedure. Recordings were conducted in a quiet room in Tianjin using an M-Audio® mobile digital audio recorder MicroTrack II with 44.1 kHz sampling rate and 16 bit rate in mono channel.

96 disyllabic items (4 initial tones∗4 final tones∗3 structures∗2 focus conditions) were elicited from each of the six participants, each with two repetitions. 768 trisyllabic items (4 initial tones∗4 middle tones∗4 final tones∗3 structures∗2 words∗2 focus conditions) were also elicited from each participant. However, one third of the items, with fricative onsets at the second or third syllable, were produced only once. The other two-thirds, with non-fricative onsets, were produced twice.

2.4. f0 analysis

The acoustic data were manually segmented in Praat (Boersma & Weenink, 2011). A custom-written script was used for *f*0 extraction and smoothing. *f*0 contours were obtained by taking 20 points (in Hertz) in the rhyme part of each syllable or in the whole syllable for the second syllable within disyllabic constituents where the syllable onsets were all sonorant. To eliminate the pitch range difference due to gender and to better illustrate the tonal variation patterns, each speaker's raw *f*0 data were normalized by converting them to speaker-specific *z*-scores (Rose, 1987). The plotted tonal contours were then based on the mean *z*-scores averaged across speakers.

2.5. Growth curve analysis

To better understand the varying nature of *f*0 over the time-course of the tone-bearing syllable, we employed the growth curve analysis (Mirman, 2014) with the package *lme4* (Bates, Maechler, Bolker, & Walker, 2014) in R (R Core Team, 2014). The growth curve analysis is a multilevel regression technique which is more appropriate and powerful for analyzing non-linear time-varying data (e.g., *f*0). The advantage of this technique is that the overall *f*0 contours are taken into consideration. Moreover, the experimental manipulations are better examined by taking into consideration of the random variation due to different subjects.

In growth curve analysis, a non-linear curve is typically fitted with high order orthogonal polynomials, such as, $y = a + bx + cx^2 + dx^3 + ex^4 \dots$ (*x* for time, *y* for *f*0). The characteristics of a curve could be independently reflected by the coefficients for different time terms in the polynomials. Among them, the intercept *a* usually indicates the overall mean of a curve; the linear term *b* indicates the general direction of the curve change (slope); the higher order terms generally reflect the curve complexity (e.g., the quadratic term *c* for a U-shape curve, cubic *d* for an S-shape curve, and quartic term *e* for a W-shape curve).

In this study, we used up to second-order polynomials since the most complex *f*0 contour of one lexical tone in our data has only a convex or concave contour shape. Tonal variation due to different contextual conditions was therefore analyzed by assessing the intercept, linear, and quadratic terms in the fitted model. If two contours differ from each other, we should expect statistical significance in at least one aspect of their *f*0 contours. This includes the overall *f*0 mean indexed by the intercept, the direction of *f*0 change such as rising vs. falling indexed by the slope, and the steepness of *f*0 rising or falling indexed by the quadratic term.

To carry out the growth curve analyses, separate linear mixed-effects models were built for subsets of the data for specific hypothesis testing. For both disyllabic and trisyllabic datasets, we have controlled the tone category, consonant type, vowel height and syllable structure for each syllable within one stimulus. We also controlled the structure (i.e., morpho-syntactic structure for disyllables and grouping structure for trisyllables), focus, repetition and relative familiarity of each stimulus. To determine which controlled factor should be considered in the models, each base model was first established containing only the time terms in the fixed factor structure and the random slope of subject on all time terms. Additional controlled factors were then added in the models in a stepwise fashion. Model fits were tested at each step via model comparisons based on the change in the log-likelihood ratios.
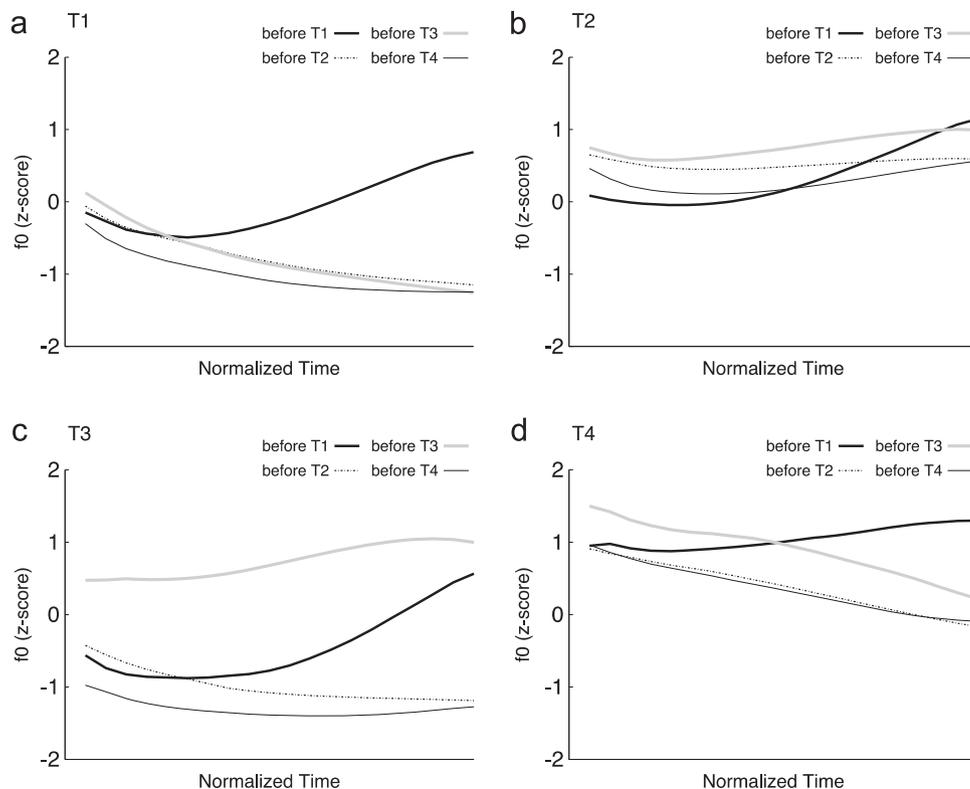

Fig. 2. The *f*0 variation of the four target lexical tones due to different following tones. T1 in (a), T2 in (b), T3 in (c) and T4 in (d). Lines indicate the mean of the normalized *f*0 contour across speakers. Normalized time.

Table 2
Results of pairwise comparison on the variability in the first tone due to different following tones. *a* for Target T1, *b* for Target T2, *c* for Target T3, *d* for Target T4.

a. Target T1

BeforeT2 vs. beforeT1		BeforeT3 vs. beforeT1		BeforeT4 vs. beforeT1	
Intercept	Estimate$= -0.67$ $z= -6.69$, $p<0.001$	*Intercept*	Estimate$= -0.65$ $z= -5.88$, $p<0.001$	*Intercept*	Estimate$= -0.89$ $z= -8.86$, $p<0.001$
Slope	Estimate$= -2.86$ $z= -11.56$, $p<0.001$	*Slope*	Estimate$= -3.18$ $z= -12.83$, $p<0.001$	*Slope*	Estimate$= -2.55$ $z= -10.37$, $p<0.001$
Quadratic	Estimate$= -0.43$ $z= -4.13$, $p<0.001$	*Quadratic*	n.s.	*Quadratic*	Estimate$= -0.33$ $z= -3.24$, $p<0.05$
		BeforeT3 vs. beforeT2		BeforeT4 vs. beforeT2	
		Intercept	n.s.	*Intercept*	n.s.
		Slope	n.s.	*Slope*	n.s.
		Quadratic	n.s.	*Quadratic*	n.s.
				BeforeT4 vs. beforeT3	
				Intercept	n.s.
				Slope	n.s.
				Quadratic	n.s.

b. Target T2

BeforeT2 vs. beforeT1		BeforeT3 vs. beforeT1		BeforeT4 vs. beforeT1	
Intercept	n.s.	*Intercept*	n.s.	*Intercept*	Estimate$= -0.43$ $z= -3.77$, $p<0.01$
Slope	Estimate$= -1.58$ $z= -8.17$, $p<0.001$	*Slope*	Estimate$= -0.98$ $z= -5.04$, $p<0.001$	*Slope*	Estimate$= -1.19$ $z= -6.12$, $p<0.001$
Quadratic	Estimate$= -0.45$ $z= -6.32$, $p<0.001$	*Quadratic*	Estimate$= -0.48$ $z= -6.42$, $p<0.001$	*Quadratic*	Estimate$= -0.24$ $z= -3.28$, $p<0.05$
		BeforeT3 vs. beforeT2		BeforeT4 vs. beforeT2	
		Intercept	Estimate$=0.32$ $z=3.29$, $p<0.05$	*Intercept*	n.s.
		Slope	Estimate$=0.60$ $z=3.06$, $p<0.05$	*Slope*	n.s.
		Quadratic	n.s.	*Quadratic*	n.s.
				BeforeT4 vs. beforeT3	
				Intercept	Estimate$= -0.53$ $z= -5.38$, $p<0.001$
				Slope	n.s.
				Quadratic	Estimate$=0.24$ $z=3.22$, $p<0.05$

c. Target T3

BeforeT2 vs. beforeT1		BeforeT3 vs. beforeT1		BeforeT4 vs. beforeT1	
Intercept	Estimate$= -1.04$ $z= -6.66$, $p<0.001$	*Intercept*	n.s.	*Intercept*	Estimate$= -0.95$ $z= -6.25$, $p<0.001$
Slope	Estimate$= -2.54$ $z= -8.71$, $p<0.001$	*Slope*	Estimate$= -0.88$ $z= -3.04$, $p<0.05$	*Slope*	Estimate$= -2.16$ $z= -7.47$, $p<0.001$
Quadratic	Estimate$= -0.66$ $z= -5.37$, $p<0.001$	*Quadratic*	Estimate$= -0.95$ $z= -7.82$, $p<0.001$	*Quadratic*	Estimate$= -0.64$ $z= -5.37$, $p<0.001$
		BeforeT3 vs. beforeT2		BeforeT4 vs. beforeT2	
		Intercept	Estimate$=1.47$ $z=9.29$, $p<0.001$	*Intercept*	n.s.
		Slope	Estimate$=1.66$ $z=5.69$, $p<0.001$	*Slope*	n.s.
		Quadratic	n.s.	*Quadratic*	n.s.
				BeforeT4 vs. beforeT3	
				Intercept	Estimate$= -1.39$ $z= -8.84$, $p<0.001$
				Slope	Estimate$= -1.28$ $z= -4.42$, $p<0.001$
				Quadratic	n.s.

d. Target T4

BeforeT2 vs. beforeT1		BeforeT3 vs. beforeT1		BeforeT4 vs. beforeT1	
Intercept	Estimate$= -0.53$ $z= -19.64$, $p<0.001$	*Intercept*	n.s.	*Intercept*	Estimate$= -0.48$ $z= -16.03$, $p<0.001$

Table 2 (*continued*)

d. Target T4					
Slope	Estimate = −2.02 z = −21.61, *p* < 0.001	*Slope*	Estimate = −2.18 z = −23.99, *p* < 0.001	*Slope*	Estimate = −2.03 z = −22.25, *p* < 0.001
Quadratic	n.s.	*Quadratic*	Estimate = −0.40 z = −4.31, *p* < 0.001	*Quadratic*	n.s.
		BeforeT3 vs. beforeT2		BeforeT4 vs. beforeT2	
		Intercept	Estimate = 0.52 z = 19.84, *p* < 0.001	*Intercept*	n.s.
		Slope	n.s.	*Slope*	n.s.
		Quadratic	n.s.	*Quadratic*	n.s.
				BeforeT4 vs. beforeT3	
				Intercept	Estimate = −0.46 z = −18.07, *p* < 0.001
				Slope	n.s.
				Quadratic	n.s.

Controlled factors that significantly improved the model fits were kept in the fixed factor structure of the models. Parameter-specific *p*-values were estimated using the normal approximation (i.e., treating the *t*-value as a *z*-value). Multiple comparisons with Bonferroni adjustment were conducted with the function *glht* in package *multcomp* (Hothorn, Bretz, & Westfall, 2008) whenever necessary.

3. Results and discussion I: tonal variation in disyllabic domain

3.1. Results

We were interested in the potential differences in tonal variation due to coarticulation and tone sandhi. Given that tone sandhi of disyllabic sequences in Tianjin Mandarin involves the modification of the first tone as a function of its following tone, we zoomed into the *f*0 contours of each first tone followed by different second tones (i.e., the anticipatory effects), as plotted in Fig. 2. For our planned comparisons, the whole disyllabic dataset was separated into four subsets according to the tonal category of the first tone. The statistical results were summarized in Table 2.

3.1.1. T1Tx
As shown in Fig. 2a, the first T1 remains as a low-falling tone except when it is followed by another T1, in which case, it surfaces with a rising *f*0 contour. This difference was statistically significant, as supported by results in Table 2a, where the *f*0 contour of T1 before another T1 showed a significant difference from that before the other tones. (See significant statistical results of target T1 beforeT2 vs. beforeT1, beforeT3 vs. beforeT1, and beforeT4 vs. beforeT1.) For T1 before T2, T3, and T4, however, we did not see any significant difference. (See the lack of significant results of target T1 beforeT3 vs. beforeT2, beforeT4 vs. beforeT2, and beforeT4 vs. beforeT3.)

3.1.2. T2Tx
Fig. 2b shows that, the first T2 remains a high-rising tone regardless of the identity of the following tone. There are, however, some subtle differences restricted to two contexts, i.e., before T1 and T3.
Before T1, there was a slight yet consistent *f*0 rise towards the end of the tone-bearing syllable compared to that before the other three tones, confirmed by the significant statistical results in the slope and quadratic components in Table 2b. (See target T2 beforeT2 vs. beforeT1, beforeT3 vs. beforeT1, beforeT4 vs. beforeT1.) The raising effect before T1 on T2 was somehow different from the raising effect of T3 on T2. When followed by a T3, there was an overall raising effect of the whole *f*0 mean contour, which was supported by the significant results in the intercept. (See target T2 beforeT3 vs. beforeT2 and beforeT4 vs. beforeT3.) In addition, there were some slight and less consistent contour differences when T2 was followed by T3, compared to that followed by T2 and T4 (reflected in the significant results of slope in target T2 beforeT3 vs. beforeT2 and quadratic component in target T2 beforeT4 vs. beforeT3). There was no significant difference in the *f*0 contours of T2 beforeT2 vs. beforeT4.

3.1.3. T3Tx
Fig. 2c shows that the target T3 varies greatly as a function of the following tones, which again were restricted mainly to two contexts, i.e., before T1 and T3. Before T1, there was a consistently greater *f*0 rise compared to that before the other three tones, as confirmed by the significant results in the slope and quadratic components in Table 2c. (See target T3 beforeT2 vs. beforeT1, beforeT3 vs. beforeT1, beforeT4 vs. beforeT1.) This is different from the general T3 raising effect before another T3, which was

mainly confirmed by the significant intercept differences. (See target T3 beforeT3 vs. beforeT2 and beforeT4 vs. beforeT3.) This T3 raising effect is similar to what we have observed for the raising effect of T3 on the preceding target T2, but with a much greater magnitude. In addition, probably due to the slightly falling f0 before T2 and T4, we also observed a significant difference in the slope. (See again target T3 beforeT3 vs. beforeT2, beforeT4 vs. beforeT3.)

3.1.4. T4Tx

Fig. 2d shows that the variation of T4 was also restricted to the two following tonal contexts, i.e., T1 and T3, as observed for targets T2 and T3 earlier. T1 again, introduced a significantly greater f0 rise on its preceding T4 in terms of significant slope differences shown in Table 2d, in addition to the less consistent intercept and quadratic differences. (See target T4 beforeT2 vs. beforeT1, beforeT3 vs. beforeT1, beforeT4 vs. beforeT1.) Before T3, T4 showed a more general overall f0 raising effect, as indicated by the significantly different intercepts. (See target T4 beforeT3 vs. beforeT2 and beforeT4 vs. beforeT3.) There was no significant difference in the f0 contours of T4 before T2 vs. T4.

3.2. Discussion

Within disyllabic tonal sequences, we have observed a range of variation in the f0 realization of four lexical tones due to different following tones. The results were summarized in Table 3, where within a disyllabic tonal sequence, the first tone was affected in terms of both the overall f0 mean as well as the f0 contour shape.

With regard to the overall f0 mean, all tones (except T1) were significantly raised by the following T3 compared to those preceding other tones. It is important to note that the raising over T3 was significantly greater than that over T2 and T4. In terms of f0 contour change, what we observed was the consistent f0 rise over all lexical tones that preceded T1. Their magnitudes of f0 rise were fairly comparable regardless of the identity of the target tones.

As introduced earlier, there is consensus in the literature that T1T1, T4T1, and T3T3 undergo tone sandhi changes (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Hyman, 2007). T4T3 has been reported to involve anticipatory tonal coarticulation (Zhang & Liu, 2011). Furthermore, it has been proposed in the literature that T3T2, T3T4 and T4T4 also involve tone sandhi (see Wee et al., 2005; Zhang & Liu, 2011 for T3T2 and T3T4 sandhi; see Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Hyman, 2007 for T4T4 sandhi). Our results showed that there was no significant tonal alternation in T3T2, T3T4, and T4T4, raising questions to the application of tone sandhi over these sequences. Instead, we observed a clear f0 contour raising effect of T1 on T2 and T3 (Fig. 2b and c) as well as a general raising effect of T3 on T2 (Fig. 2b), which have never been reported in the literature either as a tone sandhi change or as contextual tonal coarticulation.

Traditionally, tone sandhi in Tianjin Mandarin has always been characterized as the categorical change of one lexical tone to another within the lexical tone inventory (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Hyman, 2007). With the three tonal sequences that have been claimed to undergo tone sandhi (i.e., T1T1, T4T1, T3T3), which did show contextual tonal variation in our data, we further examined whether they involved categorical sandhi changes into T2/T3T1, T2T1 and T2T3, respectively. Our approach was to compare the f0 contours of the three sandhi sequences to the f0 realization of their respective targeted outputs claimed in the literature (i.e., T1T1 vs. T2/T3T1, T4T1 vs. T2T1 and T3T3 vs. T2T3).

Plotted in Fig. 3 are the f0 contours of the three sandhi sequences (in dark gray) against the f0 contours of their respective claimed targeted outputs (in light gray). Specifically, T1T1 (against T2/T3T1) is shown in Fig. 3a, T4T1 (against T2T1) in Fig. 3b, and T3T3 (against T2T3) in Fig. 3c. Statistical results of their planned comparisons are summarized in Table 4.

Fig. 3 shows that all the three tonal sequences were produced significantly differently from their claimed targeted outputs, as confirmed by significant statistical results in Table 4. Our results thus confirmed the non-neutralization in the three disyllabic tonal sequences as found in Zhang and Liu (2011). Apparently, tonal neutralization cannot be the criterion of what constitutes tone sandhi. The question is then what differentiates tone sandhi from phonetic tonal coarticulation?

Table 3
Summary of variability in the first tone due to different following tones.

| 1st Tone	2nd Tone			
	T1 (low-falling)	T2 (high-rising)	T3 (low-dipping)	T4 (high-falling)
T1 (low-falling)	Greater f0 rise	No effect	No effect	No effect
T2 (high-rising)	Greater f0 rise	No effect	Slightly raised overall f0 contour	No effect
T3 (low-dipping)	Greater f0 rise	No effect	Greatly raised overall f0 contour; Small f0 rise	No effect
T4 (high-falling)	Greater f0 Rise	No effect	Slightly raised overall f0 contour	No effect
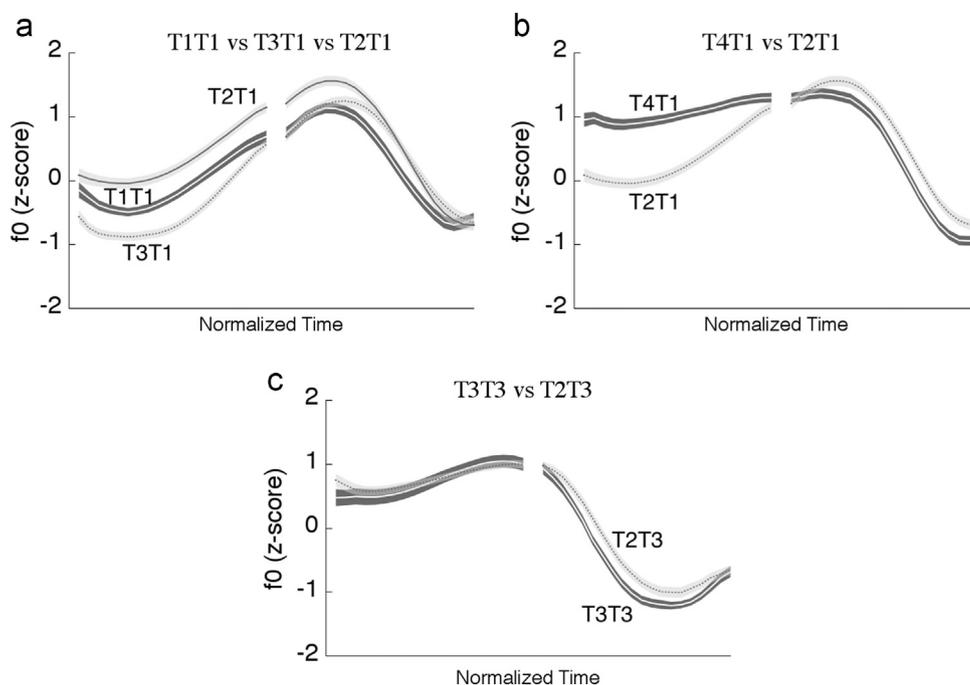
Fig. 3. The *f*0 realization of the three confirmed disyllabic sandhi patterns. White thick lines indicate the mean *f*0 of the disyllabic sandhi sequences (dark gray areas for ±1 standard error of mean); black lines indicate the mean *f*0 of the claimed targeted output (light gray areas for ±1 standard error of mean). Normalized time.

Table 4
Results of growth curve analyses for T1T1 vs. T2T1/T3T1, T4T1 vs. T2T1, T3T3 vs. T2T3. Bolded items for tones under comparison.

	T1T1		T4T1	T3T3
	T3T1 vs. **T1**T1	**T2**T1 vs. **T1**T1	**T4**T1 vs. **T2**T1	**T3**T3 vs. **T2**T3
Intercept	Estimate = −0.41 *t* = −12.87, *p* < 0.001	Estimate = 0.22 *t* = 8.69, *p* < 0.001	Estimate = 0.71 *t* = 19.52, *p* < 0.001	n.s.
Slope	n.s.	n.s.	Estimate = −1.02 *t* = −11.42, *p* < 0.001	Estimate = 0.25 *t* = 2.81, *p* < 0.01
Quadratic	Estimate = 0.27 *t* = 2.66, *p* < 0.01	n.s.	Estimate = −0.48 *t* = −5.37, *p* < 0.001	n.s.

Generally speaking, phonetic coarticulation caused by the following tone should not affect the distinctiveness of a lexical tonal contour (e.g., Gandour et al., 1994; Xu, 1997), so that its characteristic *f*0 contour can still be expected to accord with its canonical tonal shape. A phonological tone sandhi alternation, however, usually brings about major changes in the *f*0 contour of a lexical tone so that its surface *f*0 may be unpredictable from the characteristics of the canonical tonal *f*0 contour. Among the seven disyllabic cases that exhibited a statistically significant amount of tonal variance as shown in Table 3, both falling tones T1 and T4 were realized with rising *f*0 contours due to the contour raising effect triggered by the following T1 (i.e., in T1T1 and T4T1); the low-dipping T3 was realized with a high *f*0 register due to the general raising effect from the following T3 (i.e., in T3T3). These altered *f*0 realizations were unpredictable from its canonical low tones, and therefore seemed justified to be categorized as tone sandhi. In the other four cases, i.e., T3T1, T2T1, T2T3, T4T3, however, the *f*0 realization of the first tone was rather recognizable despite variation due to the following tone. It is not clear therefore whether a sandhi rule is necessary for these four cases.

To summarize, we have confirmed three disyllabic tonal sequences to be tone sandhi patterns as reported in the literature, i.e., T1T1, T4T1 and T3T3 (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Ma, 2005; Hyman, 2007). We also found a significant anticipatory raising effect, though with minor modifications, on T2 and T4 before T3, as well as a significant contour raising effect on T2 and T3 before T1. All other tonal sequences were found to induce non-significant (probably perceptually negligible) phonetic changes.

Note that even for the confirmed tone sandhi cases, it is clear that sandhi does not involve categorical change of one lexical tone to another. The lack of tonal neutralization makes it clear that tone sandhi in Tianjin Mandarin should not be characterized as the categorical change of one lexical tone to another. Such a lack of categorical sandhi change also raises serious doubts on the tonal variation patterns of trisyllabic constituents reported in the literature.

4. Results and discussion II: tonal variation in trisyllabic domain

In this section, we examined tonal variation in Tianjin Mandarin over trisyllabic domains. We limited our attention to the three disyllabic sandhi processes confirmed so far and investigated how these sandhi changes are applied in trisyllabic sequences. Each trisyllabic sequence was compared to the targeted output pattern as claimed in the literature. Table 5 concludes all the sandhi-involved trisyllabic combinations discussed in the literature based on the three disyllabic processes. (Some combinations might appear twice in this table due to the fact that some disyllabic patterns are involved in more than one trisyllabic combinations.) We separated our analyses according to the classification of simple vs. complex tone sandhi contexts proposed in the literature. In the simple sandhi contexts, the directionality of sandhi application was investigated whereas in the complex sandhi contexts (bolded), we aimed to tap into the iterativity of sandhi application in addition to the directionality.

Table 5
All trisyllabic tone sandhi combinations proposed in the literature involving T1T1, T4T1 and T3T3. The bold items are those possibly involving complex tonal contexts.

	T1T1		T4T1		T3T3	
	Left-aligned	Right-aligned	Left-aligned	Right-aligned	Left-aligned	Right-aligned
T1	**T1T1T1**		**T4T1T1**	T1T4T1	T3T3T1	T1T3T3
T2	T1T1T2	T2T1T1	T4T1T2	T2T4T1	T3T3T2	T2T3T3
T3	T1T1T3	**T3T1T1**	T4T1T3	T3T4T1	**T3T3T3**	
T4	T1T1T4	**T4T1T1**	T4T1T4	T4T4T1	T3T3T4	T4T3T3
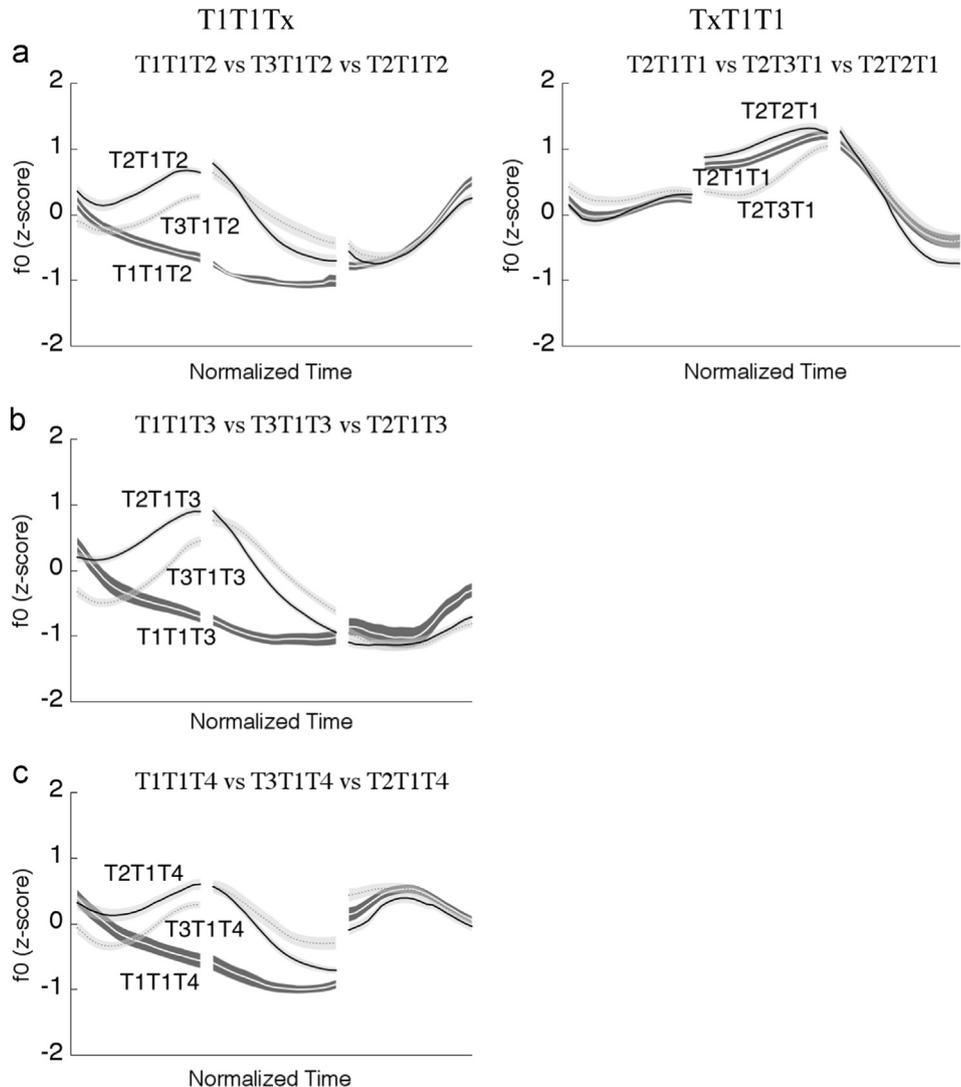
Fig. 4. Trisyllabic sandhi contexts containing T1T1. White thick lines indicate the mean f0 patterns of the trisyllabic sandhi sequences (dark gray areas for ± 1 standard error of mean); black dotted lines indicate the mean f0 patterns of the claimed targeted output containing T3T1 (light gray areas for ± 1 standard error of mean); black thick lines indicate the mean f0 patterns of the claimed targeted output containing T2T1 (light gray areas for ± 1 standard error of mean). Normalized time.

4.1. Simple sandhi contexts

We set up the simple sandhi contexts as aligning a disyllabic sandhi tonal sequence either to the left or right of a trisyllabic constituent, without involving potentially multiple applications of tone sandhi. In Figs. 4–6, the $f0$ contours of the trisyllabic sequences (in dark gray) were compared to the $f0$ realization of their respective sandhi targeted outputs as claimed in the literature (in light gray). Note that those plotted on the left have the sandhi contexts in the first two syllables (left-aligned); and those on the right have the sandhi contexts in the last two syllables (right-aligned). Merged $f0$ contours are expected if there is neutralization in tone sandhi. Again, for the case of T1T1, both T2T1 and T3T1 were included given that both possibilities have been proposed in the literature. The statistical results are summarized in Tables 6–8.
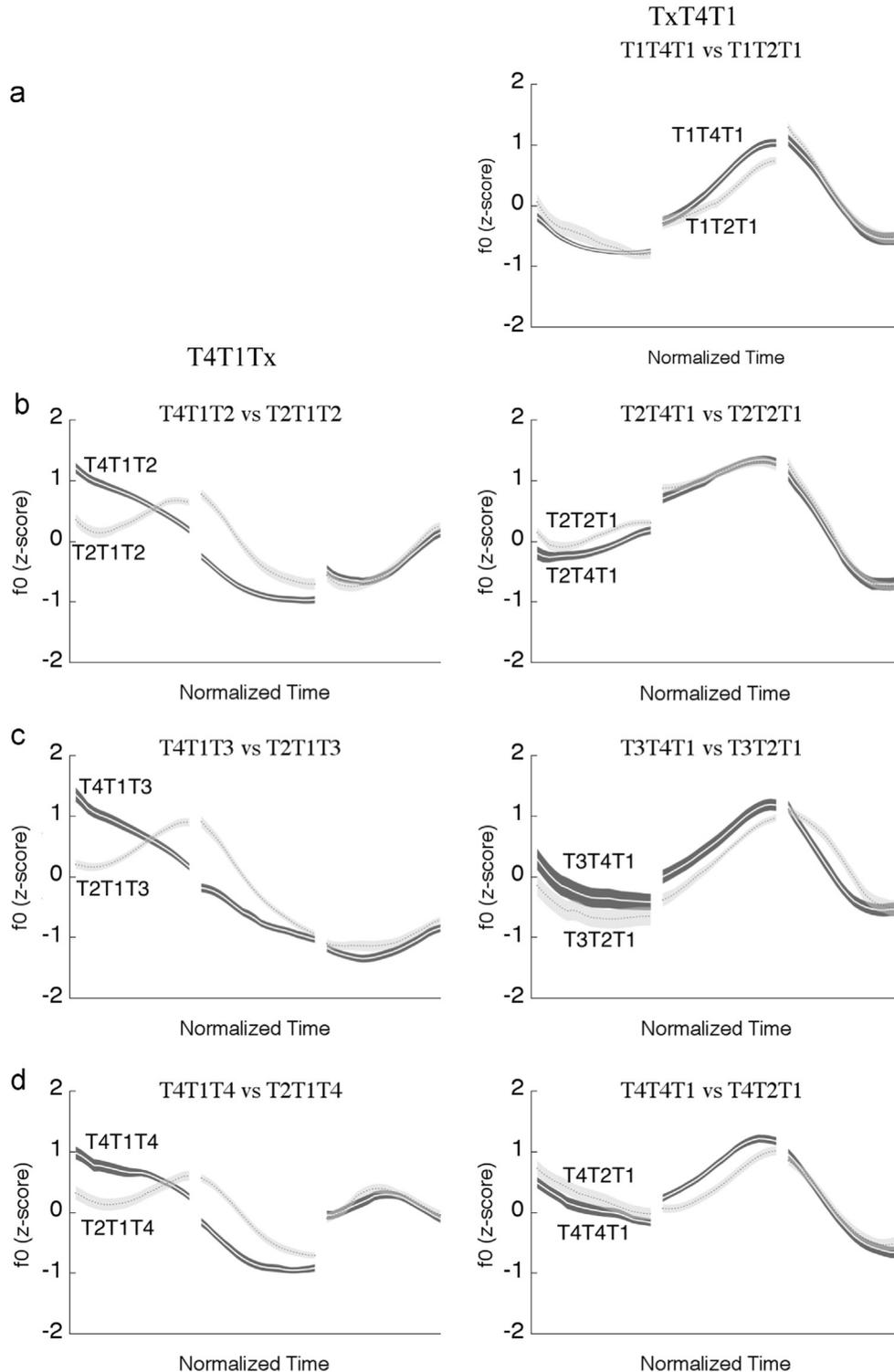

Fig. 5. Trisyllabic sandhi contexts containing T4T1. White thick lines indicate the mean $f0$ patterns of the trisyllabic sandhi sequences (dark gray areas for ± 1 standard error of mean) and black dotted lines indicate the mean $f0$ patterns of the claimed targeted outputs (light gray areas for ± 1 standard error of mean). Normalized time.
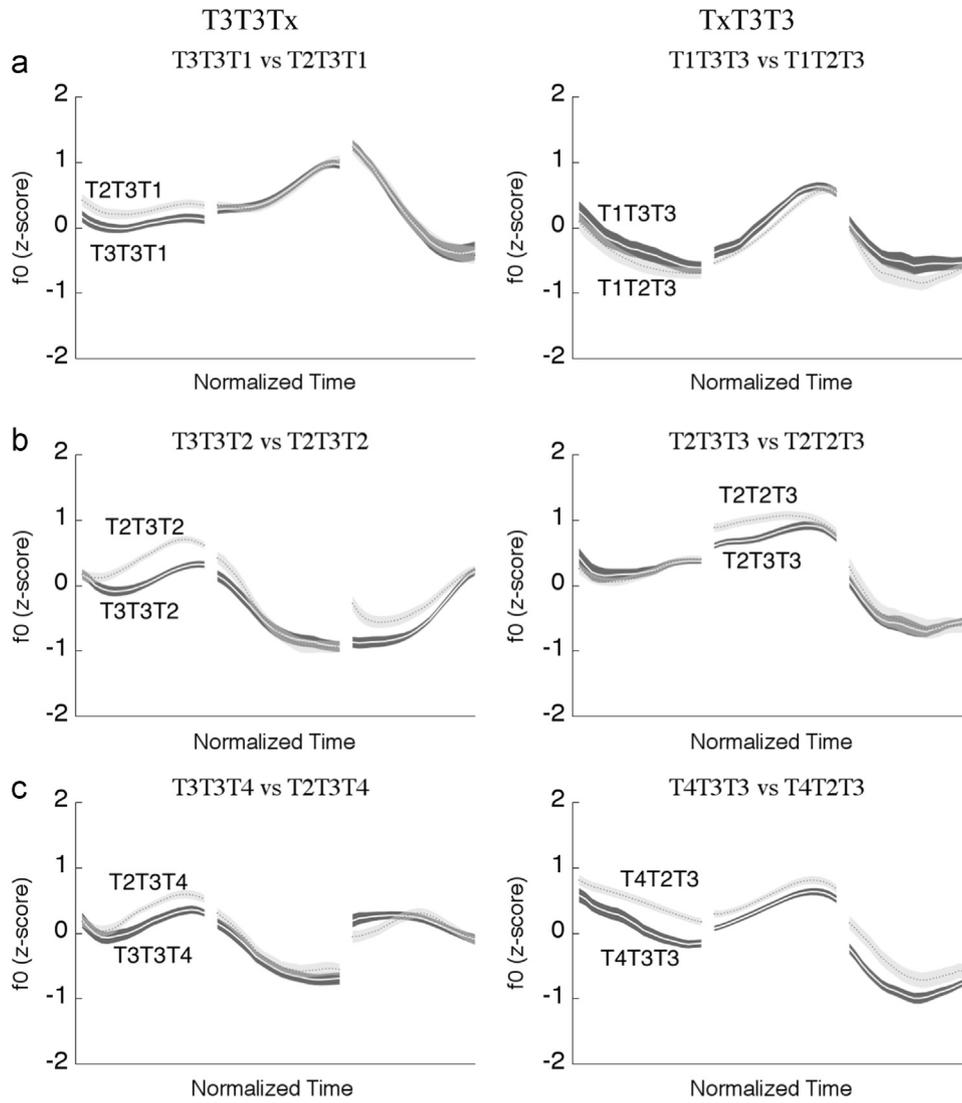
Fig. 6. Trisyllabic sandhi contexts containing T3T3. White thick lines indicate the mean $f0$ patterns of the trisyllabic sandhi sequences (dark gray areas for ± 1 standard error of mean) and black dotted lines indicate the mean $f0$ patterns of the claimed targeted outputs (light gray areas for ± 1 standard error of mean). Normalized time.

Table 6
Results of growth curve analyses for T1T1Tx vs. TxT1T1. Bolded items for tones under comparison.

	T1T1Tx		TxT1T1	
	T1T1T2 vs. T2T1T2	T1T1T2 vs. T3T1T2	T2T1T1 vs. T2T2T1	T2T1T1 vs. T2T3T1
Intercept	Estimate=0.93 t=38.35, p<0.001	Estimate=0.56 t=18.91, p<0.001	n.s.	Estimate=-0.28 t=-13.05, p<0.001
Slope	Estimate=1.78 t=19.69, p<0.001	Estimate=1.73 t=19.06, p<0.001	n.s.	Estimate=0.36 t=4.09, p<0.001
Quadratic	n.s.	n.s.	Estimate=-0.21 t=-2.36, p<0.05	Estimate=0.29 t=3.26, p<0.01
	T1T1T3 vs. **T2**T1T3	**T1**T1T3 vs. **T3**T1T3		
Intercept	Estimate=1.05 t=21.10, p<0.001	Estimate=0.47 t=10.87, p<0.001		
Slope	Estimate=2.48 t=21.15, p<0.001	Estimate=2.63 t=22.46, p<0.001		
Quadratic	n.s.	n.s.		
	T1T1T4 vs. **T2**T1T4	**T1**T1T4 vs. **T3**T1T4		
Intercept	Estimate=0.91 t=26.35, p<0.001	Estimate=0.50 t=11.53, p<0.001		
Slope	Estimate=1.77 t=14.67, p<0.001	Estimate=2.04 t=16.82, p<0.001		
Quadratic	n.s.	n.s.		

4.1.1. *T1T1Tx vs. TxT1T1*

As shown in Fig. 4, the application of T1T1 sandhi can only be observed when T1T1 is right aligned. However, the sandhi-T1 was not neutralized with either T3 or T2. The non-neutralization pattern confirms what we have observed in disyllabic T1T1 tonal sequences. Specifically, when T1T1 was left aligned (i.e., T1T1T2, T1T1T3, T1T1T4 in Fig. 4a–c, left column), the first T1 was clearly realized with a falling f0 contour, which was the opposite of that of T2/T3, as confirmed by the significant differences in the slope (see

Table 7
Results of growth curve analyses for T4T1Tx vs. TxT4T1. Bolded items for tones under comparison.

	T4T1Tx	TxT4T1
		T1T4**T1** vs. T1**T2**T1
Intercept		Estimate$=0.25$, $t=7.71$, $p<0.001$
Slope		Estimate$=0.48$, $t=4.83$, $p<0.001$
Quadratic		Estimate$=-0.25$, $t=-2.49$, $p<0.05$
	T4T1T2 vs. **T2**T1T2	T2**T4**T1 vs. T2**T2**T1
Intercept	Estimate$=0.17$, $t=4.40$, $p<0.001$	Estimate$=0.05$, $t=2.42$, $p<0.05$
Slope	Estimate$=-2.05$, $t=-24.07$, $p<0.001$	Estimate$=0.25$, $t=2.89$, $p<0.01$
Quadratic	Estimate$=-0.31$, $t=-3.68$, $p<0.001$	n.s.
	T4T1T3 vs. **T2**T1T3	T3**T4**T1 vs. T3**T2**T1
Intercept	n.s.	Estimate$=0.30$, $t=3.48$, $p<0.01$
Slope	Estimate$=-3.00$, $t=-32.89$, $p<0.001$	n.s.
Quadratic	Estimate$=-0.33$, $t=-3.71$, $p<0.001$	n.s.
	T4T1T4 vs. **T2**T1T4	T4**T4**T1 vs. T4**T2**T1
Intercept	Estimate$=0.71$, $t=17.13$, $p<0.001$	n.s.
Slope	Estimate$=-1.41$, $t=-12.88$, $p<0.001$	n.s.
Quadratic	Estimate$=-0.41$, $t=-3.77$, $p<0.001$	Estimate$=-0.36$, $t=-4.25$, $p<0.001$

Table 8
Results of growth curve analyses for T3T3Tx vs. TxT3T3. Bolded items for tones under comparison.

	T3T3Tx	TxT3T3
	T3T3T1 vs. **T2**T3T1	T1**T3**T3 vs. T1**T2**T3
Intercept	n.s.	Estimate$=-0.55$, $t=-11.47$, $p<0.001$
Slope	n.s.	n.s.
Quadratic	n.s	Estimate$=-0.19$, $t=-2.45$, $p<0.05$
	T3T3T2 vs. **T2**T3T2	T2**T3**T3 vs. T2**T2**T3
Intercept	Estimate$=-0.09$, $t=-2.87$, $p<0.01$	Estimate$=-0.07$, $t=-2.03$, $p<0.05$
Slope	Estimate$=-0.45$, $t=-5.98$, $p<0.001$	Estimate$=0.33$, $t=4.54$, $p<0.001$
Quadratic	Estimate$=0.42$, $t=5.54$, $p<0.001$	n.s.
	T3T3T4 vs. **T2**T3T4	T4**T3**T3 vs. T4**T2**T3
Intercept	Estimate$=-0.29$, $t=-8.45$, $p<0.001$	Estimate$=-0.14$, $t=-7.35$, $p<0.001$
Slope	Estimate$=-0.33$, $t=-3.57$, $p<0.001$	n.s.
Quadratic	Estimate$=0.23$, $t=2.50$, $p<0.05$	n.s.

T1T1Tx in Table 6). When T1T1 was right aligned as in T2T1T1 (Fig. 4a, right), the middle T1 was realized with a rising *f*0 contour, suggesting the application of tone sandhi (Fig. 3a). However, the significant statistical results suggested no tonal neutralization between the middle T1 vs. its claimed output T2 or T3 (see T1T1Tx in Table 6).

4.1.2. T4T1Tx vs. TxT4T1

As shown in Fig. 5, T4T1 also undergoes tone sandhi only when it is right aligned, as observed earlier for T1T1. Again, no tonal neutralization was confirmed between T4 and its claimed output T2. Specifically, when T4T1 was left aligned (i.e., T4T1T2, T4T1T3, T4T1T4 in Fig. 5a–c, left column), tone sandhi could not have applied, given its falling *f*0 contour. This was confirmed by the significant slope difference between T2 and T4 in all the left-aligned cases (T4T1Tx in Table 7). When T4T1 was right aligned (i.e., T1T4T1, T2T4T1, T3T4T1, T4T4T1 in Fig. 5a–d, right), the rising *f*0 contour over the T4-bearing syllable suggested the application of tone sandhi (as comparable to that in disyllabic sequences shown in Fig. 3b), but again no neutralization was confirmed. See significant statistical results of the *f*0 differences between TxT4T1 vs. TxT2T1, summarized in Table 7.

4.1.3. T3T3Tx vs. TxT3T3

Fig. 6 displays the T3T3 sequence in the left-aligned contexts (T3T3T1, T3T3T2, T3T3T4 in Fig. 6a–c, left) and the right-aligned contexts (T1T3T3, T2T3T3, T4T3T3 in Fig. 6a–c, right). Note that T3T3T3 will be discussed in Section 4.2.1 due to its potentially complex tone sandhi application. In both T3T3Tx and TxT3T3, the first T3 showed a rising *f*0 contour, suggesting the consistent application of the T3 sandhi, as observed in disyllabic T3T3 sequence (Fig. 3c). However, sandhi-T3 showed significant differences from T2 in all the other tonal contexts (see significant results in both T3T3Tx and TxT3T3 in Table 8), except for the sequence T3T3T1. This confirmed again the general lack of complete neutralization in these tone sandhi cases.

4.2. Complex sandhi contexts

Four trisyllabic sequences have been claimed to involve potentially more complex sandhi changes, due to the so-called iterative process of tone sandhi application (e.g., Chen, 2000). Note that the iterative process of sandhi application stems from the assumption in the literature that tone sandhi in Tianjin Mandarin involves the categorical change of one lexical tone to another, which leads to iterative sandhi application due to a new sandhi context resulting from the first round of sandhi application.

Given that T3T3 sandhi applies both when left aligned and right aligned, while T1T1 and T4T1 show sandhi change only when right aligned, we examined the possibilities listed in Table 9, where the bolded cases have been reported in the literature. Our results should shed light on two issues. One concerns the directionality of tone sandhi application when both directions provide sandhi contexts. The other concerns iterative sandhi application. For ease of exposition, we followed the sandhi rules claimed in the literature, and described the targeted outputs as results of the iterativity of sandhi application where the intermediate step would create a new tone sandhi context (i.e., if tone sandhi indeed involved categorical change of one lexical tone to another). Statistical results were shown in Tables 10–12.

4.2.1. T3T3T3

For the combination T3T3T3, both directions of sandhi application are possible. According to the claimed rules in the literature, both T2T2T3 (from the left) and T3T2T3 (from the right) are possible outputs, where a chain effect is expected if the sandhi rule is applied from the left edge through an intermediate stage T2T3T3. Fig. 7 compares the three possible outcomes (Fig. 7a from left; Fig. 7b from right). As can be seen from Fig. 7, T3T3 sandhi was more likely to be applied from the left edge rather than from the right.

For the left-aligned sandhi application possibilities (Fig. 7a), T3T3T3 was similar to both T2T3T3 and T2T2T3, but was not completely neutralized with either. T3T3T3 and T2T3T3 were significantly different in terms of the mean *f*0 of the first tone. (See significant results for T3T3T3 vs. T2T3T3 in Table 10a.) T3T3T3 and T2T2T3 differed even more. There were significant differences in the overall *f*0 mean and slope of both the first and second tones. (See significant results for T3T3T3 vs. T2T2T3 in Table 10a.) However, given the similarity of the contour shapes, it is likely that the second T3 changed to T2 in T3T3T3, although it is difficult to pin down that there was sandhi application over the second T3 given that the two contours were nevertheless quite different.

Turning to the right-aligned sandhi possibility (Fig. 7b), T3T3T3 and T3T2T3 were significantly different in the overall *f*0 mean and the slope for both the first and second tones. (See significant results of the intercept for T3T3T3 vs. T3T2T3 in Table 10b.) The significant and salient *f*0 differences between the two tonal sequences suggest that T3 sandhi was unlikely to be applied from the right edge.

Table 9
Possible targeted outputs of complex tonal contexts according to the literature. The bolded items for patterns reported in the literature.

	From the left		From the right	
T3T3T3	(1st Round) **T2T3T3**	(2nd Round) **T2T2T3**	T3T2T3	
T3T1T1	No sandhi		(1st Round) **T3T3T1**	(2nd Round) **T2T3T1**
T1T1T1	No sandhi		**T1T3T1**	
T4T1T1	No sandhi		**T4T3T1**	

Table 10
Results of growth curve analyses for T3T3T3 vs. T2T3T3/T3T2T3/T2T2T3.

	a. Left-aligned		*b.* Right-aligned	
	T3T3T3 vs. T2T3T3 1st Tone		T3T3T3 vs. T3T2T3 1st Tone	T3T3T3 vs. T2T3T3 2nd Tone
Intercept	Estimate=0.21 t=4.97, p<0.001		Estimate=0.38 t=6.89, p<0.001	Estimate=0.85 t=20.06, p<0.001
Slope	n.s.		Estimate=0.39 t=2.53, p<0.05	Estimate=−0.99 t=−11.61, p<0.001
Quadratic	n.s.		n.s.	n.s.
	T3T3T3 vs. T2T2T3			
	1st Tone	2nd Tone		
Intercept	Estimate=−0.12 t=−4.38, p<0.001	Estimate=0.47 t=7.88, p<0.001		
Slope	Estimate=−0.23 t=−2.49, p<0.05	Estimate=0.52 t=6.26, p<0.001		
Quadratic	n.s.	n.s.		

Table 11
Results of growth curve analyses for T3T1T1 vs. T3T3T1/T2T3T1.

	a. Left-aligned T3T1T1 vs. T3T3T1		*b.* Right-aligned T3T1T1 vs. T2T3T1	
	1st Tone	2nd Tone	1st Tone	2nd Tone
Intercept	n.s.	Estimate=0.46 t=14.32, p<0.001	Estimate=−0.72 t=−20.30, p<0.001	Estimate=0.24 t=11.48, p<0.001
Slope	Estimate=0.98 t=7.00, p<0.001	Estimate=−1.20 t=−14.39, p<0.001	Estimate=−0.94 t=−6.70, p<0.001	Estimate=−1.12 t=−13.23, p<0.001
Quadratic	n.s.	n.s.	n.s.	Estimate=0.30 t=3.55, p<0.001

Table 12
Results of growth curve analyses for T1T1T1 vs. T1T3T1 and T4T1T1 vs. T4T3T1. Bolded items for tones under comparison.

	T1**T1**T1 vs. T1**T3**T1	T4**T1**T1 vs. T4**T3**T1
Intercept	Estimate=−0.40, t=−14.23, p<0.001	Estimate=−0.96, t=−16.26, p<0.001
Slope	Estimate=−0.62, t=−6.77, p<0.001	Estimate=−0.54, t=−7.04, p<0.001
Quadratic	n.s.	n.s.
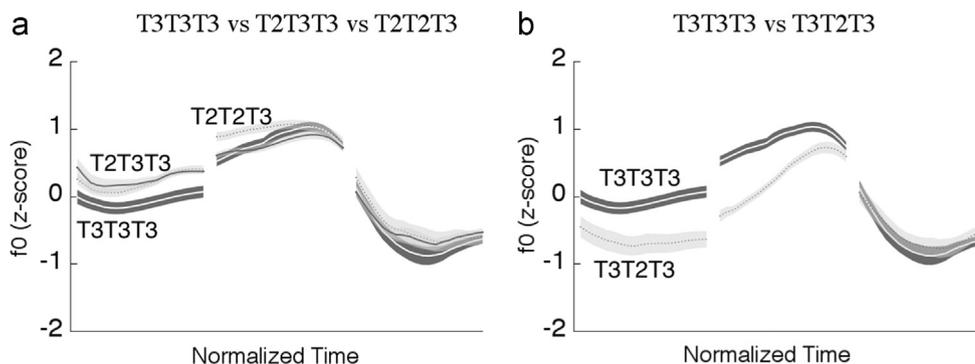
Fig. 7. The comparison of two possible directions of tone sandhi application in the sequence T3T3T3. White thick lines indicate the mean $f0$ patterns of T3T3T3 in both graphs (dark gray areas for ± 1 standard error of mean) and black dotted lines indicate the mean $f0$ patterns of the claimed targeted outputs with different directionalities (light gray areas for ± 1 standard error of mean). Graph (a) indicates the left-initial direction and Graph (b) the right-initial direction. Normalized time.

4.2.2. T3T1T1

For T3T1T1, the literature has claimed iterative sandhi application initiated from the right edge through an intermediate stage T3T3T1 which in turn changes to T2T3T1, as shown in the second row of Table 9. In Fig. 8, the surface f0 pattern of T3T1T1 was compared to that of both potential outputs.

First, in Fig. 8, the first T3 in T3T1T1 was realized with a low-falling contour, which was significantly different from the rising f0 over T2 or T3. (See significant results in the slopes of the first tone for T3T1T1 vs. T3T3T1 and T3T1T1 vs. T2T3T1 in Table 11.) Second, the middle tone in T3T1T1 was realized with a rising f0 contour, which indicates the application of tone sandhi here (compared to Fig. 3a). However, the middle T1 was not fully neutralized with the claimed output T3 in either T3T3T1 or T2T3T1. (See significant results for T3T1T1 vs. T3T3T1 and T3T1T1 vs. T2T3T1 in Table 11.) This suggests one-step tone sandhi from the right edge for T3T1T1, without any chain effect.

4.2.3. T1T1T1 and T4T1T1

For both T1T1T1 and T4T1T1, only one-step sandhi application from the right edge has been proposed in the literature. Fig. 9 illustrates f0 realization of the two sequences, compared to their respective claimed outputs T1T3T1 (Fig. 9a) and T4T3T1 (Fig. 9b).

In both cases, sandhi application from the right edge was confirmed, again with no complete neutralization involved. Fig. 9a shows that the middle T1 was realized with a rising f0, suggesting the application of T1T1 tone sandhi from the right edge of the trisyllabic constituent. However, it was still not neutralized with its claimed targeted output T3, as suggested by the significant differences between the middle T1 and T3. (See significant results for T1T1T1 vs. T1T3T1 in Table 12.) Similarly, tone sandhi in T4T1T1 also seemed to be applied from the right edge (Fig. 9b), without complete tonal neutralization. (See significant results for T4T1T1 vs. T4T3T1 in Table 12.)

4.3. Discussion

For trisyllabic sequences, we were interested in the issue of directionality and iterativity of tone sandhi application. We separated our data into two sets. One concerns directionality of tone sandhi application in simple contexts where only one round of sandhi application is possible. We varied the position of the sandhi sequences, either to the left or to the right edge of a trisyllabic tone sequence. What has been claimed in the literature is that in such contexts, tone sandhi in Tianjin Mandarin applies consistently regardless of the positional alignment of the tonal sequences (e.g., Li & Liu, 1985; Chen, 2000; Ma, 2005; Wee et al., 2005). Our results, however, did not support this observation. Our data showed that tone sandhi application over T1T1 and T4T1 sequences was only possible when these disyllabic sequences were aligned to the right edge of a trisyllabic constituent; while the T3T3 sequence triggered consistent application of sandhi changes regardless of its position within a trisyllabic utterance.
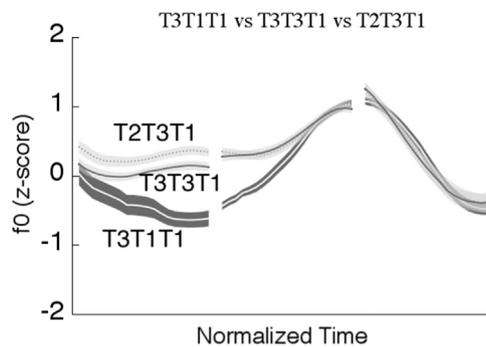
Fig. 8. The comparison of the sequences T3T1T1, T3T3T1 and T2T3T1. White thick lines indicate the mean f0 patterns of T3T1T1 (dark gray areas for ± 1 standard error of mean), black thick lines indicate the mean f0 patterns of T3T3T1 (light gray areas for ± 1 standard error of mean), black dotted lines indicate the mean f0 patterns of T2T3T1 (light gray areas for ± 1 standard error of mean). Normalized time.
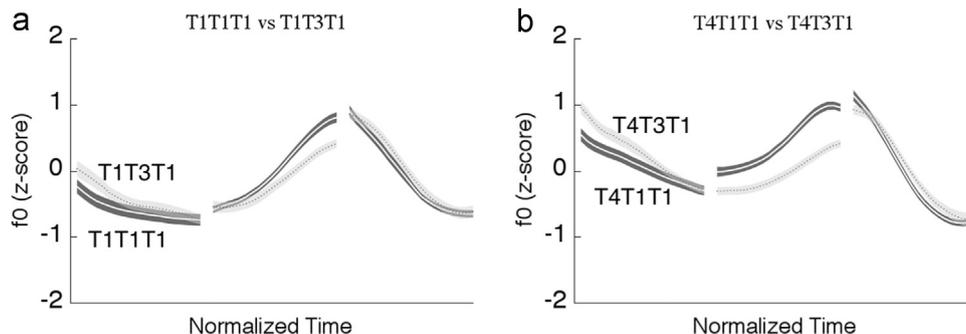
**Fig. 9.** Comparison of sequences T1T1T1 vs. T1T3T1 and T4T1T1 vs. T4T3T1. White thick lines indicate the mean f0 of the trisyllabic sandhi sequences (dark gray areas for ± 1 standard error of mean) and black dotted lines for the mean f0 of the claimed targeted outputs (light gray areas for ± 1 standard error of mean). Normalized time.

Our second set of data examined complex sandhi contexts, where the literature has claimed both different directionalities of sandhi application as well as iterative sandhi processes due to the derived sandhi context (i.e., after an initial sandhi application process over the sequence). Two findings are to be noted. One is that we indeed found directional constraints on sandhi application. For T3T3T3 sequences, we observed only left-initiated tone sandhi application, in sharp contrast with the flexibility of T3 sandhi in the simple sandhi contexts. For the T1T1 and T4T1 sequences, we confirmed our observation in the simple contexts where tone sandhi was found to apply only when they were right aligned.

The non-neutralization of sandhi application was further confirmed in our trisyllabic data. We have shown that the $f0$ realization of most trisyllabic sandhi combinations was significantly different from the claimed targeted outputs. If categorical change of one lexical tone to another was truly involved in tone sandhi, we would have expected all trisyllabic tone sandhi sequences to be realized exactly as the claimed targeted outputs. This, however, was not borne out. Furthermore, no iterativity of sandhi application was observed in our data. This lends further evidence to the argument that tone sandhi does not involve the categorical change of one lexical tone to another, which otherwise could have created a newly-derived sandhi context for another round of sandhi application.

5. General discussion and conclusions

This study illustrated the rich layers of lexical tone variability induced by different local contextual tonal variation processes, with empirical evidence from Tianjin Mandarin. Two specific questions have been addressed concerning the received wisdom of tonal variation in Tianjin Mandarin: (1) How does the $f0$ realization of a lexical tone vary as a function of different following tones within a disyllabic domain? (2) How are the disyllabic tone sandhi patterns realized in trisyllabic sequences?

5.1. Tonal variation in disyllabic domain

With regard to disyllabic sequences, we aimed to fully understand the various patterns of $f0$ deviation due to different contextual tonal variation processes, namely tonal anticipatory coarticulation and tone sandhi. To this end, we investigated all possible combinations of the four lexical tones in the language. In particular, we zoomed into the effect of the following tones (on the second syllable) on the $f0$ realization of the preceding tone (on the first syllable), because this is a comparable context to examine both tonal coarticulation and tone sandhi as Tianjin Mandarin shows right-dominant tone sandhi patterns.

With the technique of growth curve analysis (GCA), we were able to objectively quantify whether and how $f0$ contours differ from each other in terms of the overall $f0$ means, the general $f0$ direction and the $f0$ contour shape, as a function of the following lexical tones. GCA with linear mixed-effects modeling also helped to take better care of not only the time-varying nature of $f0$ contours but also variation due to individual participants. The methodology thus enabled us to better observe the $f0$ variation and gain further understanding of the different sources of $f0$ variation.

Two patterns emerged from the data, as summarized in Table 13. The first is that all significant $f0$ variation observed over the first tone is triggered by a low-register lexical tone in Tianjin Mandarin (i.e., T1 or T3). T1 induces a consistent contour raising effect, while T3 exerts a more general raising effect on the preceding tones (except for T1 followed by T3). This in part confirms the findings of Zhang and Liu (2011), which only examined however the anticipatory tonal coarticulation in T1T3, T2T3, T4T3, and T2T1, and reported a significant raising effect only in T4T3. Our study, with all tonal combinations included and more powerful statistical analyses, showed that there was also a subtle but significant raising effect in T2T1, T3T1 and T2T3.

The question that arises is why both T1 and T3 tend to raise the preceding lexical tones? Within the Sinitic family, Xu (1997) reported a rather subtle anticipatory raising effect due to the low onset of the following tone, with data from Standard Chinese. In the case of Tianjin Mandarin, though a closely related Mandarin dialect, the raising effect seems to be dialect-specific. T1 and T2 are not that different in terms of their initial $f0$ height. If anticipatory raising was purely phonetic due to the onset $f0$ value of the following tone, we should have observed similar anticipatory raising effects. Our results, however, showed that they behaved completely differently in their effects on preceding tones. It is probably the tonal register (i.e., the low register in T1 and T3) that has played a role in conditioning anticipatory raising, suggesting the possibility of phonologically-conditioned anticipatory raising effects. It is to be noted

Table 13
Summary of the contexts and tonal variability type of first tone within a disyllabic constituents.

1st Tone		2nd Tone			
		Low register		High register	
		T1	T3	T2	T4
Low register	T1	Sandhi rising	No effect	No effect	No effect
	T3	Anticipatory rising	Sandhi raising	No effect	No effect
High register	T2	Anticipatory rising	Anticipatory raising	No effect	No effect
	T4	Sandhi rising	Anticipatory raising	No effect	No effect

that significant anticipatory effects have also been reported for Malaysian Hokkien (Chang & Hsieh, 2012), where carryover and anticipatory tonal coarticulation show similar magnitude due to the final prominence of the following syllable. These language-specific patterns contribute to the typology of contextual tonal variation, with data that challenge the general asymmetrical effects of tonal coarticulation (with greater carryover effects than anticipatory effects) observed in the literature (see Chen, 2012 for a review).

Second, we observed that for the sequences T1T1, T4T1 and T3T3, they either changed the $f0$ trajectory (in the case of T1T1 and T4T1) or substantially raised the overall $f0$ register (in the case of T3T3), which indeed seem appropriate to be characterized as due to tonal sandhi (as claimed in the literature). For the other four sequences (i.e., T2T1, T3T1, T2T3, T4T3), the lexical tones were realized with an $f0$ contour that actually resembles the canonical realizations of the tones despite significant $f0$ deviation. Therefore it is not clear whether tone sandhi has been applied or whether they are better accounted for as anticipatory tonal coarticulation.

Previous impressionistic studies have claimed that T4T4 also undergoes sandhi change to T1T4 (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Ma, 2005; Hyman, 2007). Our data, however, did not show any significant $f0$ variation over T4 due to the following T4. If T4T4 underwent sandhi change, the first T4 should have surfaced with a low-register falling $f0$. On the contrary, Fig. 2d shows that the first T4 in T4T4 was realized with a high-register falling contour, similar to the T4 in T4T2 and T4T3. This is consistent with findings in recent studies (e.g., Liu & Gao, 2003; Zhang & Liu, 2011), which argued that the T4T4 sandhi process has become "obsolete", possibly due to the influence from Standard Chinese, where there is no tone sandhi over the T4T4 sequence.

When followed by T2 or T4, T3 was realized with a low-falling contour, resembling the canonical realization of T1 in isolation. This has led to the claim that T3T2 and T3T4 also involve tone sandhi change into the lexical T1 (e.g., Wee et al., 2005) or into a half T3 (Zhang & Liu, 2011).[1] Ma and Jia (2006) showed that listeners could reliably distinguish T3T2 from T1T2 and T3T4 from T1T4. Moreover, it is important to note that in our data, neither T2 nor T4 seems to introduce any anticipatory effect on its preceding tones unlike as observed for T1 and T3. We thus adopt the view that the half-realized T3 is due to tonal reduction in connected speech, which seems to be a more general phonetic reduction of dipping tone in connected speech as is also evident in Standard Chinese. However, as pointed out by one reviewer, we cannot rule out the possibility that tonal reduction is phonologized and should be classified as tone sandhi, as proposed in Zhang and Liu (2011).

There have been some attempts in the last decades to establish objective criteria to distinguish between tone sandhi and tonal coarticulation. Shen (1992) proposes a three-way distinction between the two types of tonal variation. (1) Tone sandhi is constrained by language-specific morphophonemics, while tonal coarticulation is a language-independent mechanism. (2) Tone sandhi is either assimilatory or dissimilatory, while tonal coarticulation is only assimilatory. (3) Tone sandhi involves tonal identity change from one tone to another while the tonal identity is maintained in tonal coarticulation. None of these criteria, however, really succeeded in differentiating the two processes, as also discussed in Chen (2000). First, tone sandhi and tonal coarticulation could both be affected by morphophonemics as suggested in Wu (1985). Second, cross-linguistic evidence has shown that tonal coarticulation could be either assimilatory or dissimilatory (e.g., Gandour et al., 1994 for Thai; Xu, 1997 for Beijing Mandarin; Zhang & Liu, 2011 for Tianjin Mandarin; Chang & Hsieh, 2012 for Malaysian Hokkien). Third, tone sandhi does not always involve tonal identity change. For example, in the T1T1 sequence, our results show that the first T1 is clearly not changed from T1 to T3 as claimed in the literature, but the magnitude of the change suggests the possibility of phonologization of such an anticipatory raising effect. These observations led to the proposition in Chen (2000) that there is actually "no essential difference" between the two processes.

As the boundary between tone sandhi and tonal coarticulation is not straightforward and proves difficult to establish, this makes it even more important for us to first objectively observe the patterns of $f0$ variation as we have done in the current study. Without this, any discussion over the difference between these two variation types is doomed to be without foundation.

Through the extensive comparisons of the full dataset with all four lexical tones in both the first and second syllables, we can see that the raising effects due to T3 and T1 indeed need to be further differentiated. The T3 category across Mandarin dialects is known for its sandhi process over a T3T3 sequence, regardless of the specific $f0$ contour of the lexical tone category (Shih, 1986). This process has been proposed to date back to the 16th century (Mei, 1977; also see discussion in Zhang, 2010). As for T1T1 and T4T1, a significant raising effect was observed, which is in contrast to the more subtle raising effect of T1 over T2T1 and T3T1. We believe that this difference is related to the saliency of cues for $f0$ raising before T1. In the case of two falling tones, i.e., T1 and T4, the raising effect can be effectively implemented, which probably led to an enhanced realization of $f0$ raising and consequently a phonologized contextual tonal change; while in the case of T2 and T3, both with a rising $f0$ contour in the canonical $f0$ shape, there is no further room to signal the raising due to T1, which therefore remains a more subtle coarticulatory effect.

The raising effects due to T3 and T1 can be further teased apart in terms of how closely the sandhi outputs resemble a lexical tone in the native system. T3T3 is a near-merger (following Yu, 2007), in that the derived T3 sandhi realization shows an almost merged $f0$ pattern to that of a lexical high-register rising tone, i.e., T2 in T2T3. This explains why in the literature T3T3 is described as changing into T2T3. T1T1 and T4T1, however, are clearly no-mergers. Their derived sandhi outputs are clearly different from any of the lexical tones in the system, in contradiction to the claim that they change to T3/T2T1 and T2T1 respectively. Our study, thus far, is the first to illuminate this distinction. An interesting question that is currently addressed in a perception study is how such different patterns of tone sandhi affect the way lexical tones are processed in online speech recognition.

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[1] The falling contour of T3 is also comparable to the half low tone realization in Standard Mandarin (Chao, 1968), where the final rise of the dipping T3 is always absent in non-prepausal positions (but present when followed by a neutral tone as discussed in details in Chen & Xu, 2006 and Prom-on, Liu & Xu, 2012).

Table 14
Summary of two types of tone sandhi in Tianjin Mandarin.

| | Sandhi variation over disyllabic sequences | Directionality over trisyllabic sequences | |
		Simple contexts	Complex contexts
T3T3	Near-merger	From both directions	From the left edge
T1T1	No-merger	From the right edge	
T4T1	No-merger		

5.2. Tonal variation in trisyllabic domain

Our disyllabic data established firmly that tone sandhi in Tianjin Mandarin should not be characterized as the categorical change of one lexical tone to another, confirming earlier findings in Zhang and Liu (2011) and Li and Chen (2012). This finding also led to the absolute necessity of further investigation on trisyllabic tone sandhi patterns in Tianjin Mandarin, which have raised numerous critical issues in the theoretical treatment of tone sandhi in general (e.g., Chen, 2000). Our approach was to first investigate the empirical foundation of the reported complexity in Tianjin Mandarin tone sandhi over trisyllabic sequences. To this end, we have analyzed the $f0$ realization of trisyllabic tonal combinations with two more specific goals in mind.

The first was on the directionality of sandhi application in simple tonal contexts with only one disyllabic sequence involving potential tone sandhi. The three tone sandhi sequences (i.e., T1T1, T4T1, and T3T3) were embedded in trisyllabic constituents, either left-aligned (e.g., T1T1Tx) or right-aligned (e.g., TxT1T1). Different from the claims in the literature, we observed that while T3T3 sandhi applied in either direction, T1T1 and T4T1 surfaced with their predicted sandhi $f0$ contours only when they were right aligned. This is the very first experimental finding on Tianjin trisyllabic tone sandhi. Our finding therefore greatly simplifies the hitherto claimed complex directionality of tone sandhi in Tianjin Mandarin.

Our second goal was to examine further the claimed iterativity of sandhi application, which refers to the application of tone sandhi over derived sandhi contexts due to an earlier round of tone sandhi application. Specifically, we examined the $f0$ contours of the underlying sequences of T3T3T3, T3T1T1, T1T1T1, and T4T1T1. Interestingly, we noticed a further directionality restriction over T3T3T3 sequence where T3 sandhi seemed to only apply from the left edge, resulting in the ambiguity between T3$_{sandhi}$T3T3 and T3$_{sandhi}$T3$_{sandhi}$T3. Either pattern, however, does not have to involve iterative sandhi application. Furthermore, no iterativity of sandhi application in T3T1T1 was found, even though it has been claimed in the literature that the change of T1T1 to T3T1 creates an intermediate stage T3T3T1 which triggers a further sandhi change into T2T3T1. For the other two tonal sequences concerning T1T1 (i.e., T1T1T1 and T4T1T1), our data only showed one-step tone sandhi application from the right-aligned disyllabic sequences. In short, no iterative sandhi application can be confirmed in our data.

Taking together both disyllabic and trisyllabic data, we have observed two types of tone sandhi in Tianjin Mandarin, as summarized in Table 14. T3T3 is a near-merge case. Its sandhi output T3$_{sandhi}$T3 shows an almost merged $f0$ contour with the lexical tonal sequence of T2T3. In a simple trisyllabic sandhi context, this sandhi process can occur from either direction regardless of its alignment within the constituent. However, in a complex trisyllabic sandhi context, T3T3 surfaces with a pattern that suggests only left-aligned sandhi application, resulting in an $f0$ contour that can be characterized as T3$_{sandhi}$T3T3 or T3$_{sandhi}$T3$_{sandhi}$T3. T1T1 and T4T1 can be classified as no-mergers, given that their sandhi realizations do not resemble the $f0$ contours of any of the lexical tones in the language. In contrast to T3T3, tone sandhi in T1T1 and T4T1 is applied only when the disyllabic sequence is right aligned regardless of whether the embedding trisyllabic constituent provides a simple or complex sandhi context. No iterativity of sandhi application was observed in any of these tonal sequences.

This study therefore provides a substantial amount of experimental data that greatly simplify the complex and paradoxical tone sandhi patterns reported in the literature (e.g., Li & Liu, 1985; Hung, 1987; Tan, 1987; Zhang, 1987; Chen, 2000; J. Wang, 2002; Ma, 2005; Wee et al., 2005; Zhang & Liu, 2011). We believe that our findings are not only of major empirical significance, but will also contribute to the further development of theories of tonal variation in general, as any good theory needs to be based upon solid empirical evidence. A cautionary note is that our data are representative of speakers born in the 1980s. It is possible that those tone sandhi patterns claimed in the literature can only be observed in older speakers, which then requires relevant experimental data in the future. If any generational difference is verified, it would be important to investigate the mechanisms that explain the changing sandhi patterns observed in old vs. young Tianjin Mandarin speakers as well as the implication of such tonal change mechanisms for language evolution in general.

Appendix

The full list of disyllabic and trisyllabic words used in the experiment are given below.
Disyllabic word list:

Tonal sequences	Morpho-syntactic structures					
	Compound		Modifier+head		Verb+object	
T1T1	爹妈 die^1 ma^1	*parents*	家猫 jia^1 mao^1	*domestic cat*	弯腰 wan^1 yao^1	*to bend down*
T1T2	规模 gui^1 mo^2	*scale*	歌迷 ge^1 mi^2	*fans*	猜谜 cai^1 mi^2	*to guess a riddle*
T1T3	枢纽 shu^1 niu^3	*hub*	糙米 cao^1 mi^3	*brown rice*	推理 tui^1 li^3	*to reason*
T1T4	归纳 gui^1 na^4	*to conclude*	闺蜜 gui1 mi^4	*girlfriends*	揭密 jie^1 mi^4	*to reveal a secret*
T2T1	拿捏 na^2 nie^1	*to ponder*	白猫 bai^2 mao^1	*white cat*	行医 xing^2 yi^1	*to practice medicine*
T2T2	皮毛 pi^2 mao^2	*fur*	活埋 huo^2 mai^2	*to bury alive*	回眸 hui^2 mou^2	*to look back*
T2T3	涂抹 tu^2 mo^3	*to smear*	鸵鸟 tuo^2 niao^3	*ostrich*	淘米 tao^2 mi^3	*to wash rice*
T2T4	稠密 chou^2 mi^4	*dense*	胡闹 hu^2 nao^4	*to make trouble*	夺目 duo^2 mu^4	*dazzling*
T3T1	扭捏 niu^3 nie^1	*coy*	奶妈 nai^3 ma^1	*nanny*	爽约 shuang^3 yue^1	*to fail to keep an appointment*
T3T2	楷模 kai^3 mo^2	*model*	铁牛 tie^3 niu^2	*tractor*	起锚 qi^3 mao^2	*to raise anchor*
T3T3	子女 zi^3 nü^3	*child*	舞女 wu^3 nü^3	*dancing girl*	洗脑 xi^3 nao^3	*to brainwash*
T3T4	美妙 mei^3 miao^4	*wonderful*	果木 guo^3 mu^4	*fruit tree*	把脉 ba^3 mai^4	*to take one's pulse*
T4T1	触摸 chu^4 mo^1	*to touch*	后妈 hou^4 ma^1	*step mother*	喂猫 wei^4 mao^1	*to feed the cat*
T4T2	计谋 ji^4 mou^2	*stratagem*	亚麻 ya^4 ma^2	*linen*	蓄谋 xu^4 mou^2	*to premeditate*
T4T3	购买 gou^4 mai^3	*to buy*	密码 mi^4 ma^3	*password*	喂奶 wei^4 nai^3	*to breastfeed*
T4T4	咒骂 zhou^4 ma^4	*to curse*	内幕 nei^4 mu^4	*inside story*	盗墓 dao^4 mu^4	*to rob a grave*

Trisyllabic list 1: σσσ

Tonal sequences	Word 1		Word 2	
T1T1T1	乌拉圭 wu^1 la^1 gui^1	*Uruguay*	撒哈拉 sa^1 ha^1 la^1	*Sahara*
T1T1T2	西班牙 xi^1 ban^1 ya^2	*Spain*	阿拉伯 a^1 la^1 bo^2	*Arab*
T1T1T3	希拉里 xi^1 la^1 li^3	*Hilary*	巴哈马 ba^1 ha^1 ma^3	*Bahamas*
T1T1T4	伊拉克 yi^1 la^1 ke^4	*Iraq*	科威特 ke^1 wei^1 te^4	*Kuwait*
T1T2T1	昆德拉 kun^1 de^2 la^1	*Kundera*	科伦坡 ke^1 lun^2 po^1	*Colombo*
T1T2T2	科摩罗 ke^1 mo^2 luo^2	*Comoros*	巴格达 ba^1 ge^2 da^2	*Baghdad*
T1T2T3	巴拿马 ba^1 na^2 ma^3	*Panama*	多明我 duo^1 ming^2 wo^3	*Domingo*

T1T2T4	加拿大 jia¹ na² da⁴	Canada	匈牙利 xiong¹ ya² li⁴	Hungary
T1T3T1	安卡拉 an¹ ka³ la¹	Ankara	詹姆斯 zhan¹ mu³ si¹	James
T1T3T2	苏里南 su¹ li³ nan²	Surinam	多里达 duo¹ li³ da²	Derrida
T1T3T3	托马里 tuo¹ ma³ li³	Tomari	扎卡里 zha¹ ka³ li³	Zachry
T1T3T4	多普勒 duo¹ pu³ le⁴	Doppler	冈比亚 gang¹ bi³ ya⁴	Gambia
T1T4T1	菲律宾 fei¹ lv⁴ bin¹	Philippine	阿克拉 a¹ ke⁴ la¹	Accra
T1T4T2	喀麦隆 ka¹ mai⁴ long²	Cameroon	乌克兰 wu¹ ke⁴ lan²	Ukraine
T1T4T3	哈勒姆 ha¹ le⁴ mu³	Haarlem	安道尔 an¹ dao⁴ er³	Andorra
T1T4T4	伽利略 jia¹ li⁴ lüe⁴	Galilei	巴洛克 ba¹ luo⁴ ke⁴	Baroque
T2T1T1	尼加拉 ni² jia¹ la¹	Niagara	达拉斯 da² la¹ si¹	Dallas
T2T1T2	柏拉图 bo² la¹ tu²	Plato	德黑兰 de² hei¹ lan²	Tehran
T2T1T3	博拉美 bo² la¹ mei³	Polamer	卢森堡 lu² sen¹ bao³	Luxembourg
T2T1T4	黎巴嫩 li² ba¹ nen⁴	Lebanon	明斯克 ming² si¹ ke⁴	Minsk
T2T2T1	吉隆坡 ji² long² po¹	Kuala Lumpur	俄罗斯 e² luo² si¹	Russia
T2T2T2	婆罗门 po² luo² men²	Brahman	迪德罗 di² de² luo²	Diderot
T2T2T3	德雷姆 de² lei² mu³	Dremu	尼泊尔 ni² bo² er³	Nepal
T2T2T4	尤迪特 you² di² te⁴	Udeet	格兰特 ge² lan² te⁴	Grant
T2T3T1	牙买加 ya² mai³ jia¹	Jamaica	莱比锡 lai² bi³ xi¹	Leipzig
T2T3T2	梅里达 mei² li³ da²	Merida	图瓦卢 tu² wa³ lu²	Tuvalu
T2T3T3	劳卡鲁 lao² ka³ lu³	Lokarus	伯里瓦 bo² li³ wa³	Bolivar
T2T3T4	伯努利 bo² nu³ li⁴	Bernoulli	维也纳 wei² ye³ na⁴	Vienna
T2T4T1	摩纳哥 mo² na⁴ ge¹	Monaco	伯利兹 bo² li⁴ zi¹	Belize
T2T4T2	罗纳德 luo² na⁴ de²	Ronald	卢旺达 lu² wang⁴ da²	Rwanda
T2T4T3	伯克里 bo² ke⁴ li³	Berkeley	尼日尔 ni² ri⁴ er³	Niger
T2T4T4	维克特 wei² ke⁴ te⁴	Victor	华盛顿 hua² sheng⁴ dun⁴	Washington
T3T1T1	塔波拉 ta³ bo¹ la¹	Tabora	美因兹 mei³ yin¹ zi¹	Mainz
T3T1T2	比基尼 bi³ ji¹ ni²	Bikini	马拉维 ma³ la¹ wei²	Malawi
T3T1T3	果哥里 guo³ ge¹ li³	Gogol	里斯本 li³ si¹ ben³	Lisbon
T3T1T4	法拉利 fa³ la¹ li⁴	Ferrari	索菲亚 suo³ fei¹ ya⁴	Sofia
T3T2T1	海明威 hai³ ming² wei¹	Hemingway	马尼拉 ma³ ni² la¹	Manila
T3T2T2	卡琳达 ka³ lin² da²	Kalinda	所罗门 suo³ luo² men²	Solomon
T3T2T3	马德里 ma³ de² li³	Madrid	纽伦堡 niu³ lun² bao³	Nuremberg
T3T2T4	马其顿 ma³ qi² dun⁴	Macedonia	塔吉克 ta³ ji² ke⁴	Tajik

T3T3T1	卡米拉 ka³ mi³ la¹	Camilla	马耳他 ma³ er³ ta¹	Malta
T3T3T2	马里兰 ma³ li³ lan²	Maryland	土耳其 tu³ er³ qi²	Turkey
T3T3T3	索马里 suo³ ma³ li³	Somalia	卡塔尔 ka³ ta³ er³	Qatar
T3T3T4	柬埔寨 jian³ pu³ zhai⁴	Cambodia	雅典娜 ya³ dian³ na⁴	Athena
T3T4T1	卡耐基 ka³ nai⁴ ji¹	Carnegie	瓦杜兹 wa³ du⁴ zi¹	Vaduz
T3T4T2	普契尼 pu³ qi⁴ ni²	Puccini	比利时 bi³ li⁴ shi²	Belgium
T3T4T3	马六甲 ma³ liu⁴ jia³	Malacca	马绍尔 ma³ shao⁴ er³	Marshall
T3T4T4	玛丽娜 ma³ li⁴ na⁴	Marina	以色列 yi³ se⁴ lie⁴	Isreal
T4T1T1	孟加拉 meng⁴ jia¹ la¹	Bengal	墨西哥 mo⁴ xi¹ ge¹	Mexico
T4T1T2	布拉格 bu⁴ la¹ ge²	Prague	圣基茨 sheng⁴ ji¹ ci²	Saint Kitts
T4T1T3	爱丁堡 ai⁴ ding¹ bao³	Edinburgh	奥巴马 ao⁴ ba¹ ma³	Obama
T4T1T4	麦当娜 mai¹ dang¹ na⁴	Madonna	奥斯陆 ao⁴ si¹ lu⁴	Oslo
T4T2T1	洛仑兹 luo⁴ lun² zi¹	Lorentz	慕尼黑 mu⁴ ni² hei¹	Munich
T4T2T2	不来梅 bu⁴ lai² mei²	Bremen	布隆迪 bu⁴ long² di²	Burundi
T4T2T3	洛伦佐 luo⁴ lun² zuo³	Lorenzo	立陶宛 li⁴ tao² wan³	Lithuania
T4T2T4	奥兰治 ao⁴ lan² zhi⁴	Orange	克林顿 ke⁴ lin² dun⁴	Clinton
T4T3T1	帕美拉 pa⁴ mei³ la¹	Pamela	萨瓦多 sa⁴ wa³ duo¹	Salvador
T4T3T2	布吕尼 bu⁴ lü³ ni²	Bruni	爱尔兰 ai⁴ er³ lan²	Ireland
T4T3T3	亚美里 ya⁴ mei³ li³	Amelie	曼海姆 man⁴ hai³ mu³	Mannheim
T4T3T4	布鲁诺 bu⁴ lu³ nuo⁴	Bruno	利比亚 li⁴ bi³ ya⁴	Libya
T4T4T1	洛佩兹 luo⁴ pei⁴ zi¹	Lopez	鹿特丹 lu⁴ te⁴ dan¹	Rotterdam
T4T4T2	拜占庭 bai⁴ zhan⁴ ting²	Byzantium	密克罗 mi⁴ ke⁴ luo²	Mikro
T4T4T3	瑞贝卡 rui⁴ bei⁴ ka³	Rebecca	洛丽塔 luo⁴ li⁴ ta³	Lolita
T4T4T4	奥地利 ao⁴ di⁴ li⁴	Austria	意大利 yi⁴ da⁴ li⁴	Italy

Trisyllabic list 2: σσ+σ

Tonal sequences	Word 1		Word 2	
T1T1T1	拖拉机 tuo¹ la¹ ji¹	tractor	出租车 chu¹ zu¹ che¹	taxi
T1T1T2	公安局 gong¹ an¹ ju²	police station	工商局 gong¹ shang¹ ju²	Trade and Industry Bureau
T1T1T3	拉丁舞 la¹ ding¹ wu³	Latin dance	飞机场 fei¹ ji¹ chang³	airport
T1T1T4	基督教 ji¹ du¹ jiao⁴	Christianity	夫妻店 fu¹ qi¹ dian⁴	family-run shop
T1T2T1	金鱼缸 jin¹ yu² gang¹	goldfish tank	天狼星 tian¹ lang² xing¹	Sirius
T1T2T2	乌龙球 	own goal	安全局 	Security Bureau

	wu^1 long^2 qiu^2		an^1 quan^2 ju^2	
T1T2T3	葱油饼 cong^1 you^2 bing^3	onion pancake	冰球手 bing^1 qiu^2 shou^3	hockey player
T1T2T4	资格证 zi^1 ge^2 zheng^4	certificate	侏罗纪 zhu^1 luo^2 ji^4	Jurassic
T1T3T1	资本家 zi^1 ben^3 jia^1	capitalist	风景区 feng^1 jing^3 qu^1	scenic district
T1T3T2	宗主国 zong^1 zhu^3 guo^2	suzerain	资产权 zi^1 chan^3 quan^2	property rights
T1T3T3	斑点狗 ban^1 dian^3 gou^3	Dalmatian dog	深水港 shen^1 shui^3 gang^3	deepwater harbor
T1T3T4	天主教 tian^1 zhu^3 jiao^4	Catholicism	斑马线 ban^1 ma^3 xian^4	zebra line
T1T4T1	音乐家 yin^1 yue^4 jia^1	musician	生物钟 sheng^1 wu^4 zhong^1	biochronometer
T1T4T2	机器人 ji^1 qi^4 ren^2	robot	工作狂 gong^1 zuo^4 kuang^2	workaholic
T1T4T3	登记表 deng^1 ji^4 biao^3	registration form	工艺品 gong^1 yi^4 pin^3	handicraft
T1T4T4	关帝庙 guan^1 di^4 miao^4	Temple of General Kuan	生物链 sheng^1 wu^4 lian^4	food chain
T2T1T1	楼梯间 lou^2 ti^1 jian^1	stairwell	红灯区 hong^2 deng^1 qu^1	red light district
T2T1T2	鱼肝油 yu^2 gan^1 you^2	fish oil	传播学 chuan^2 bo^1 xue^2	communication
T2T1T3	服装厂 fu^2 zhuang^1 chang^3	garment factory	流星雨 liu^2 xing^1 yu^3	meteor shower
T2T1T4	牙周病 ya^2 zhou^1 bing^4	periodontal disease	神经病 shen^2 jing^1 bing^4	psycho
T2T2T1	南极洲 nan^2 ji^2 zhou^1	Antarctica	流行歌 liu^2 xing^2 ge^1	pop song
T2T2T2	蝴蝶结 hu^2 die^2 jie^2	bow knot	直肠癌 zhi^2 chang^2 ai^2	rectum cancer
T2T2T3	篮球场 lan^2 qiu^2 chang^3	basketball court	流行语 liu^2 xing^2 yu^3	popular word
T2T2T4	能源部 neng^2 yuan^2 bu^4	Ministry of Energy	神农架 shen^2 nong^2 jia^4	(a place in Hubei Province)
T2T3T1	平板车 ping^2 ban^3 che^1	trolley	平顶山 ping^2 ding^3 shan^1	(a city in Henan Province)
T2T3T2	龙井茶 long^2 jing^3 cha^2	Longjing tea	牛仔裙 niu^2 zai^3 qun^2	jeans skirt
T2T3T3	长短腿 chang^2 duan^3 tui^3	leg length discrepancy	华表奖 hua^2 biao^3 jiang^3	Marble Pillar Award
T2T3T4	营养液 ying^2 yang^3 ye^4	nutrient	寒武纪 han^2 wu^3 ji^4	Cambrian
T2T4T1	杂技班 za^2 ji^4 ban^1	acrobatic team	杂货摊 za^2 huo^4 tan^1	grocery stall
T2T4T2	国庆节 guo^2 qing^4 jie^2	National Day	杂技团 za^2 ji^4 tuan^2	acrobatic society
T2T4T3	游乐场 you^2 le^4 chang^3	playground	玩具厂 wan^2 ju^4 chang^3	toy factory
T2T4T4	疾病册 ji^2 bing^4 ce^4	list of diseases	糖尿病 tang^2 niao^4 bing^4	diabetes
T3T1T1	闪光灯 shan^3 guang^1 deng^1	flash light	镁光灯 mei^3 guang^1 deng^1	limelight
T3T1T2	火车头 huo^3 che^1 tou^2	locomotive	母亲河 mu^3 qin^1 he^2	mother river
T3T1T3	奖金卡 jiang^3 jin^1 ka^3	bonus card	广东省 guang^3 dong^1 sheng^3	Guangdong Province
T3T1T4	火车票 huo^3 che^1 piao^4	train ticket	火车站 huo^3 che^1 zhan^4	train station
T3T2T1	主人翁 zhu^3 ren^2 weng^1	hero	里程碑 li^3 cheng^2 bei^1	milestone
T3T2T2	狗头铡 gou^3 tou^2 zha^2	kobold guillotine	北极熊 bei^3 ji^2 xiong^2	polar bear
T3T2T3	打折卡 da^3 zhe^2 ka^3	coupon	死亡谷 si^3 wang^2 gu^3	death valley

	da³ zhe² ka³		si³ wang² gu³	
T3T2T4	友情价 you³ qing² jia⁴	friendly price	恐龙蛋 kong³ long² dan⁴	dinosaur egg
T3T3T1	古董车 gu³ dong³ che¹	antique car	宝马车 bao³ ma³ che¹	BMW car
T3T3T2	火把节 huo³ ba³ jie²	torch festival	理想国 li³ xiang³ guo²	Utopia
T3T3T3	演讲稿 yan³ jiang³ gao³	speech text	总统府 zong³ tong³ fu³	president office
T3T3T4	雅宝路 ya³ bao³ lu⁴	Yabao Road	老虎凳 lao³ hu³ deng⁴	tiger bench
T3T4T1	可乐机 ke³ le⁴ ji¹	coke machine	百叶窗 bai³ ye⁴ chuang¹	venetian blind
T3T4T2	保健球 bao³ jian⁴ qiu²	bowling	乳腺癌 ru³ xian⁴ ai²	breast cancer
T3T4T3	统计表 tong³ ji⁴ biao³	statistic form	笔记本 bi³ ji⁴ ben³	notebook
T3T4T4	感叹句 gan³ tan⁴ ju⁴	exclamatory sentence	打印店 da³ yin⁴ dian⁴	print shop
T4T1T1	外交官 wai⁴ jiao¹ guan¹	diplomat	地方官 di⁴ fang¹ guan¹	local official
T4T1T2	太空船 tai⁴ kong¹ chuan²	spaceship	电机房 dian⁴ ji¹ fang²	engine room
T4T1T3	贵宾卡 gui⁴ bin¹ ka³	VIP card	便签纸 bian⁴ qian¹ zhi³	sticker
T4T1T4	外交部 wai⁴ jiao¹ bu⁴	Ministry of Foreign Affairs	太空站 tai⁴ kong¹ zhan⁴	space station
T4T2T1	地球村 di⁴ qiu² cun¹	earth village	共鸣腔 gong⁴ ming² qiang¹	resonance cavity
T4T2T2	太平洋 tai⁴ ping² yang²	Pacific Ocean	橡皮泥 xing⁴ pi² ni²	plasticine
T4T2T3	互联网 hu⁴ lian² wang³	Internet	棒球手 bang⁴ qiu² shou³	baseball player
T4T2T4	外来妹 wai⁴ lai² mei⁴	girls from other places	空格键 kong⁴ ge² jian⁴	space bar
T4T3T1	电子钟 dian⁴ zi³ zhong¹	electronic clock	样板间 yang⁴ ban³ jian¹	sample room
T4T3T2	盗版盘 dao⁴ ban³ pan²	pirated CD	电影节 dian⁴ ying³ jie²	film festival
T4T3T3	电子表 dian⁴ zi³ biao³	electronic watch	电影展 dian⁴ ying³ zhan³	movie exhibition
T4T3T4	电影票 dian⁴ ying³ piao⁴	movie ticket	电影院 dian⁴ ying³ yuan⁴	cinema
T4T4T1	纪念碑 ji⁴ nian⁴ bei¹	monument	计算机 ji⁴ suan⁴ ji¹	computer
T4T4T2	纪念堂 ji⁴ nian⁴ tang²	memorial hall	电信局 dian⁴ xin⁴ ju²	tele-comm office
T4T4T3	信用卡 xin⁴ yong⁴ ka³	credit card	记忆体 ji⁴ yi⁴ ti³	RAM
T4T4T4	数据库 shu⁴ ju⁴ ku⁴	database	计算器 ji⁴ suan⁴ qi⁴	calculator

Trisyllabic list 3: σ+σσ

Tonal sequences	Word 1		Word 2	
T1T1T1	高工资 gao¹ gong¹ zi¹	high salary	新飞机 xin¹ fei¹ ji¹	new aircraft
T1T1T2	新中国 xin¹ zhong¹ guo²	new China	多功能 duo¹ gong¹ neng²	multi-function
T1T1T3	宽肩膀 kuan¹ jian¹ bang³	wide shoulder	光污染 guang¹ wu¹ ran³	light pollution
T1T1T4	轻音乐 qing¹ yin¹ yue⁴	light music	新花样 xin¹ hua¹ yang⁴	new trick

T1T2T1	干蹄筋 gan^1 ti^2 jin^1	dry tendon	双职工 shuang^1 zhi^2 gong^1	working parents
T1T2T2	东柏林 dong^1 bo^2 lin^2	East Berlin	西柏林 xi^1 bo^2 lin^2	west Berlin
T1T2T3	新油桶 xin^1 you^2 tong^3	new oil tank	鲜牛奶 xian^1 niu^2 nai^3	fresh milk
T1T2T4	新邮件 xin^1 you^2 jian^4	new mail	新词汇 xin^1 ci^2 hui^4	new vocabulary
T1T3T1	湿纸巾 shi^1 zhi^3 jin^1	wet tissue	清辅音 qing^1 fu^3 yin^1	voiceless consonant
T1T3T2	猪口条 zhu^1 kou^3 tiao^2	pig tongue	金耳环 jin^1 er^3 huan^2	gold earring
T1T3T3	新总统 xin^1 zong^3 tong^3	new president	新产品 xin^1 chan^3 pin^3	new product
T1T3T4	亲姐妹 qin^1 jie^3 mei^4	blood sister	新产业 xin^1 chan^3 ye^4	new industry
T1T4T1	湿面巾 shi^1 mian^4 jin^1	wet facial tissue	新校区 xin^1 xiao^4 qu^1	new campus
T1T4T2	猪大肠 zhu^1 da^4 chang^2	pig intestine	新纪元 xin^1 ji^4 yuan^2	new era
T1T4T3	新电影 xin^1 dian^4 ying^3	new movie	花大姐 hua^1 da^4 jie^3	ladybug
T1T4T4	新概念 xin^1 gai^4 nian^4	new concept	中世纪 zhong^1 shi^4 ji^4	middle age
T2T1T1	团中央 tuan^2 zhong^1 yang^1	league center	毛蜘蛛 mao^2 zhi^1 zhu^1	hairy spider
T2T1T2	红蜻蜓 hong^2 qing^1 ting^2	red dragonfly	瓷花瓶 ci^2 hua^1 ping^2	ceramic vase
T2T1T3	红糙米 hong^2 cao^1 mi^3	red rice	零增长 ling^2 zeng^1 zhang^3	zero increase
T2T1T4	咸鸭蛋 xian^2 ya^1 dan^4	salty duck egg	皮车座 pi^2 che^1 zuo^4	feather seat
T2T2T1	蓝瓷砖 lan^2 ci^2 zhuan^1	blue ceramic tile	男同胞 nan^2 tong^2 bao^1	fellow men
T2T2T2	前王朝 qian^2 wang^2 chao^2	previous dynasty	明长城 ming^2 chang^2 cheng^2	Ming Great Wall
T2T2T3	毒苹果 du^2 ping^2 guo^3	toxic apple	男旗手 nan^2 qi^2 shou^3	male flag-bearer
T2T2T4	咸白菜 xian^2 bai^2 cai^4	salty cabbage	雌杨树 ci^2 yang^2 shu^4	female poplar
T2T3T1	纯酒精 chun^2 jiu^3 jing^1	pure alcohol	浊辅音 zhuo^2 fu^3 yin^1	voiced consonant
T2T3T2	红嘴唇 hong^2 zui^3 chun^2	red lip	蓝宝石 lan^2 bao^3 shi^2	sapphire
T2T3T3	前总统 qian^2 zong^3 tong^3	former president	男保姆 nan^2 bao^3 mu^3	male nanny
T2T3T4	蓝孔雀 lan^2 kong^3 que^4	blue peacock	雌孔雀 ci^2 kong^3 que^4	female peacock
T2T4T1	男卫兵 nan^2 wei^4 bing^1	male guard	白衬衫 bai^2 chen^4 shan^1	white shirt
T2T4T2	红气球 hong^2 qi^4 qiu^2	red balloon	南半球 nan^2 ban^4 qiu^2	south hemisphere
T2T4T3	源代码 yuan^2 dai^4 ma^3	source code	红墨水 hong^2 mo^4 shui^3	red ink
T2T4T4	全自动 quan^2 zi^4 dong^4	automatic	全世界 quan^2 shi^4 jie^4	entire world
T3T1T1	假观音 jia^3 guan^1 yin^1	fake Buddha	党中央 dang^3 zhong^1 yang^1	party center
T3T1T2	小家庭 xiao^3 jia^1 ting^2	small family	紫蜻蜓 zi^3 qing^1 ting^2	purple dragonfly
T3T1T3	伪君子 wei^3 jun^1 zi^3	hypocrite	水污染 shui^3 wu^1 ran^3	water pollution
T3T1T4	冷空气 leng^3 kong^1 qi^4	cold air	总司令 zong^3 si^1 ling^4	general commander
T3T2T1	假投资 jia^3 tou^2 zi^1	fake investment	假结婚 jia^3 jie^2 hun^1	fake marriage

T3T2T2	小提琴 xiao³ ti² qin²	*violin*	老同学 lao³ tong² xue²	*old classmate*
T3T2T3	镁离子 mei³ li² zi³	*magnesium ion*	钾离子 jia³ li² zi³	*potassium ion*
T3T2T4	软白菜 ruan³ bai² cai⁴	*soft cabbage*	软实力 ruan³ shi² li⁴	*soft power*
T3T3T1	女主播 nü³ zhu³ bo¹	*anchorwoman*	死火山 si³ huo³ shan¹	*dead volcano*
T3T3T2	老党员 lao³ dang³ yuan²	*old party member*	小老头 xiao³ lao³ tou²	*little old man*
T3T3T3	女总统 nü³ zong³ tong³	*female president*	女总理 nü³ zong³ li³	*female prime minister*
T3T3T4	紫孔雀 zi³ kong³ que⁴	*purple peacock*	小眼镜 xiao³ yang³ jing⁴	*small glasses*
T3T4T1	小汽车 xiao³ qi⁴ che¹	*small car*	水立方 shui³ li⁴ fang¹	*Water Cube*
T3T4T2	伪政权 wei³ zheng⁴ quan²	*puppet regime*	女队员 nü³ dui⁴ yuan²	*female member*
T3T4T3	老电影 lao³ dian⁴ ying³	*old movie*	伪政府 wei³ zheng⁴ fu³	*puppet government*
T3T4T4	假面具 jia³ mian⁴ ju⁴	*guise*	小报告 xiao3 bao4 gao4	*secret report*
T4T1T1	硬钢盔 ying⁴ gang¹ kui¹	*hard helmet*	市中心 shi⁴ zhong¹ xin¹	*city center*
T4T1T2	旧中国 jiu⁴ zhong¹ guo²	*old China*	大家庭 da⁴ jia¹ ting²	*big family*
T4T1T3	负增长 fu⁴ zeng¹ zhang³	*negative increase*	重金属 zhong⁴ jin¹ shu³	*heavy metal*
T4T1T4	旧家具 jiu⁴ jia¹ ju⁴	*old furniture*	半封建 ban⁴ feng¹ jian⁴	*semi-feudal*
T4T2T1	半元音 ban⁴ yuan² yin¹	*semi-vowel*	大熊猫 da⁴ xiong² mao¹	*giant panda*
T4T2T2	臭流氓 chou⁴ liu² mang²	*hooligan*	大结局 da⁴ jie² ju²	*finale*
T4T2T3	热牛奶 re⁴ niu² nai³	*hot milk*	负离子 fu⁴ li² zi³	*anion*
T4T2T4	辣白菜 la⁴ bai² cai⁴	*spicy cabbage*	大屏幕 da⁴ ping² mu⁴	*large screen*
T4T3T1	厚脚跟 hou⁴ jiao³ gen¹	*thick heel*	副主编 fu⁴ zhu³ bian¹	*vice editor-in-chief*
T4T3T2	厚脸皮 lou⁴ lian³ pi²	*cheeky*	代总裁 dai⁴ zong³ cai²	*acting CEO*
T4T3T3	臭老九 chou⁴ lao³ jiu³	*intellectual*	大拇指 da⁴ mu³ zhi³	*thumb*
T4T3T4	旧广告 jiu⁴ guang³ gao⁴	*old commercial*	电暖器 dian⁴ nuan³ qi⁴	*heater*
T4T4T1	亚健康 ya⁴ jian⁴ kang¹	*sub-health*	电饭锅 dian⁴ fan⁴ guo¹	*rice cooker*
T4T4T2	热气球 re⁴ qi⁴ qiu²	*hot air balloon*	热炕头 re⁴ kang⁴ tou²	*heated bed*
T4T4T3	废报纸 fei⁴ bao⁴ zhi³	*waste newspaper*	木地板 mu⁴ di⁴ ban³	*wooden floor*
T4T4T4	慢动作 man⁴ dong⁴ zuo⁴	*slow motion*	半自动 ban⁴ zi⁴ dong⁴	*semi-automatic*

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